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CHAMBER GAS SECONDARY INJECTION
THRUST VECTOR CONTROL
FOR
HIGH PERFORMANCE SOLID ROCKET MOTORS

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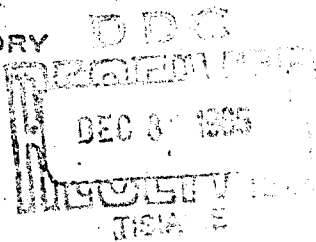
Second Quarterly Progress Report

AIR FORCE ROCKET PROPULSION LABORATORY

Research and Technology Division

Edwards Air Force Base, California

Air Force Systems Command, United States Air Force

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SPECIAL NOTICES

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CHAMBER GAS SECONDARY INJECTION THRUST VECTOR CONTROL
FOR HIGH PERFORMANCE SOLID ROCKET MOTORS (U)

28 July through 27 October 1965

November 1965

Prepared for

AIR FORCE ROCKET PROPULSION LABORATORY
Edwards Air Force Base, California

Submitted by

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FOREWORD

(U) This is the second quarterly progress report (ABL Report No. ABL/AF/QPR-4) issued under Contract AF 04(611)-10748, Program Structure No. 750G, Project No. 3059, and covers the period 28 July through 27 October 1965. Its submission date is November 12, 1965. The contract is monitored by the Air Force Rocket Propulsion Laboratory, Edwards California, and the Air Force Project Officer is Capt. Alan Higgins, RPMC.

(U) The contract, assigned to Hercules Powder Company, is being performed at Allegany Ballistics Laboratory, Box 210, Cumberland, Maryland. Mr. D. G. Drewry is the Program Supervisor.

(U) This report includes information extracted from one other classified document which is specifically identified as Reference 1 in this publication. Sources for the original data are ABL Research Notebooks 1184, 1351, 1352, 1353, 1360, X-14 and X-15.

(U) Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

(U) Because of the current nature of this report, information contained herein is frequently preliminary and fragmentary and may occasionally be inaccurate or erroneous. This laboratory reserves the right at any time to withdraw, alter or contradict any statement or data contained in this or any report of this series.

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ABSTRACT

(U)   The primary objectives of this program are (1) to demonstrate a
thrust vector control (TVC) system optimized for overall propulsion
efficiency for advanced upper-stage ICBM rocket motors and (2) to provide
the data and technology necessary for design of future TVC systems. The
proposed TVC system is comprised of four poppet valves mounted 90° apart on
a submerged nozzle. The program is divided into two consecutive phases:
Phase A - Component Development and Evaluation, and Phase B - System
Demonstration. This Technical Report describes the work performed during
the second quarter of program activity.

(U)   Three nonactuated versions of the submerged hot gas valve were
evaluated by static testing. The primary difference between the three
designs was the length of the dam enshrouding the centerbody and pintle
in the subsonic portion of the valve.

(U)   The first valve, utilizing a half-length dam which enshrouded
only the aft portion of the centerbody with its enclosed pintle, was tested
for 32 seconds at an average chamber pressure of 261 psia with 21% aluminized
CMDB propellant gas. The design proved unsatisfactory because of extensive
erosion on the centerbody and ejection of the pintle at 22 seconds.

(U)   The dam was eliminated in the second valve and the design was
tested for 6.5 seconds at an average pressure of 543 psia with the same
propellant formulation. Eliminating the graphite dam corrected the problem
of centerbody erosion but excessive erosion of the AHDG graphite pintle
shell was noted. With the exception of pintle erosion, the overall valve
design was proved to be structurally adequate.

(U)   A third valve with a full length dam (geometrically similar to
previous successful HPC/ABL "in-line" poppet valves) was tested for 6.25
seconds at an average pressure of 522 psia with propellant formulation as
before. Although char and erosion of the major parts of the valve were
within design allowances, the full length dam did not significantly alter
particle trajectories since erosion of the graphite pintle shell was similar
(22 mils/sec lengthwise average) to that experienced in the second valve
tested.

(U)   With the exception of excessive pintle erosion, it appears that
the contractually specified criteria for valve selection can be met with
the basic three-strut-supported, open (no dam) valve as used in test num-
ber 2. Results to date indicate that the pintle erosion problem is not
insurmountable but will require concentrated effort to resolve.

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I

INTRODUCTION

(U) This is the second Technical Report submitted by Hercules Powder Company, Allegany Balliatics Laboratory, to the Air Force under Contract AF 04(611)-10748, Chamber Gas Secondary Injection Thrust Vector Control (SITVC) for High Performance Solid Rocket Motors. This report covers the second three-month period of the program.

(U) The objectives of the program are to demonstrate a lightweight chamber gas secondary injection thrust vector control system optimized for overall propulsion efficiency for an upper stage solid propellant rocket motor. The program is to provide design data and technology on flight weight SITVC systems and components needed for future ICBM upper stage propulsion systems.

(C) The proposed TVC system[1] consists of four poppet valve assemblies mounted 90° apart on the submerged portion of the rocket motor. This system will bleed propellant gas from the chamber through the nozzle wall into the expanding axial gas stream to provide the side force required for thrust vector control. DDP propellant, a 20% aluminized, composite-modified, double-base composition, will be used in this investigation.

(U) The program is divided into two phases as follows: Phase A - Component Development and Evaluation, and Phase B - System Demonstration.

(U) In the initial portions of Phase A, which were completed and reported during the first quarter of this program, the TVC system design was reviewed and detailed mechanical designs of the valve and test components were made. The Technical Report for this period[1] contains a system optimization study for a chamber bleed secondary injection thrust vector control system of a generalized ICBM upper stage motor. The results of this study are being used as the basis for this project. Additionally, the design details were presented for the components for Phase A, including a full-scale valve, a subscale nozzle, control system, and a test motor.

(U) This report for the second quarter contains the results of testing three nonactuated valve configurations as originally recorded in Allegany Ballistics Laboratory Notebooks Nos. 1184, 1351, 1352, 1353, 1360, X-14 and X-15. The first valve proved unsatisfactory, and as a result, two additional valves with minor modifications were fabricated and tested under Hercules sponsorship to support this project. These tests, made to evaluate the specific design, showed that improvements are required.

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(U) Upon demonstration of an adequate design by nonactuated valve test, a 30-second prototype valve firing will be made with an actuated valve mounted on a subscale nozzle. Following this test, necessary design refinements will be made, and two 60-second firings of the actuated valve mounted on a subscale nozzle will be conducted to demonstrate the acceptability of the design.

(U) In Phase B of the program, a single test with two quadrants of thrust vector control will be made at sea level conditions using a multi-component thrust stand. Information obtained from this test will provide a basis for predicting TVC performance at altitude conditions and technology for design of future systems.

(This page is unclassified)

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II

DISCUSSION OF RESULTS

(U) Three nonactuated versions of the submerged hot gas valve were evaluated by static testing. Each valve was a poppet type with a strut-supported centerbody housing the movable pintle. In each case, gas flow modulation was controlled by the throttling area formed between the pintle and the adjacent valve seat. The primary difference between the three designs was the length of the graphite dam enshrouding the centerbody and the subsonic portion of the valve. The dam serves as a flow-directing and flow-straightening device in the gas-accelerating region of the valve. The first valve had a dam which enshrouded only the aft portion of the centerbody with its enclosed pintle; the dam was eliminated in the second valve; while in the third valve, the dam was extended to enshroud the full length of the centerbody.

(U) The first valve design was tested for 32 seconds at an average pressure of 261 psia and proved unsatisfactory because of extensive erosion on the centerbody with subsequent ejection of the pintle at 22 seconds. The erosion pattern for this valve indicated that the half-length dam was causing direct impingement of the particle-laden gas on the asbestos phenolic centerbody and was not directing gas flow in the manner predicted. Prior to ejection at 22 seconds, the AHDG graphite pintle shell experienced average lengthwise erosion at a calculated rate of approximately 25 mils/sec. This amounts to approximately 15 mils/sec normal to the eroding surface. The reason for the large deviation between this rate and the predicted erosion rate of 0.5 mil/sec has not been fully determined at this time. Thermocouple data indicate that, prior to ejection, the pintle's internal structure was adequately protected.

(U) The second nonactuated valve was tested at an average pressure of 543 psia for 6-1/2 seconds, a time considered adequate to determine the improvement in valve design to be gained by eliminating the dam. With the exception of the pintle, the post-firing condition of the valve was satisfactory. Char and erosion depths of the major phenolic parts were as predicted; however, the exposed end of the pintle's heat-treated AHDG graphite shell experienced lengthwise erosion at a calculated average rate of 27 mils/sec. As expected, eliminating the graphite dam corrected the problem of excessive erosion on the centerbody; however, pintle erosion remained excessive. In addition, the exposed phenolic face of the pintle was dished-out in a manner indicative of back flow and turbulence in the wake of the pintle. The unexpected loss of material in this area could have contributed to the high rate of pintle erosion. The test showed the valve design to be structurally adequate but the pintle lacked erosion resistance.

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(U) The third nonactuated valve (incorporating a full-length dam) was tested at an average pressure of 522 psia for 6.25 seconds. Post-firing condition of the centerbody was satisfactory and within design allowance for erosion and char at predicted rates. Because of the higher design gas velocity, average erosion and char rates along the side of the centerbody were approximately 7 mils/sec and 8 mils/sec, respectively, greater than those experienced by Valve No. 2. The full-length dam did not significantly alter particle trajectories since erosion of the pintle's graphite shell was similar (22 mils/sec lengthwise average) to that experienced in Valve No. 2. A dished-out erosion pattern was again noted on the phenolic face of the pintle. The structural integrity of the valve design was again shown to be adequate with the exception of excessive pintle erosion.

(C) Although the results obtained in these firings have not been completely evaluated at the time of this writing, it appears that with the exception of excessive pintle erosion, the criteria for valve selection (as established in Exhibit A of the contractual document) can be met with the "no-dam" valve design tested. The primary criterion for design selection is valve survivability under the following operating conditions:

(a) Firing duration   60 seconds

(b) Minimum chamber pressure 600 psia

(c) Flame temperature   6200°F (minimum)

(d) Valve response   4 cps - full amplitude

(e) Modulation capability   from 2% to 100% of valve flow

Secondary criteria that must be considered are as follows:

(a) Valve weight

(b) TVC system envelope

(c) Design simplicity

(C) The primary criterion which is most affected by the high pintle erosion experienced thus far is modulation capability from 2% to 100% of valve flow. Results to date indicate that this problem is not insurmountable but will require concentrated effort to resolve.

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CONCLUSIONS AND RECOMMENDATIONS

Conclusions

(U) The following preliminary conclusions are based on the work performed to date in this program:

1. A valve design which provides a minimum path length adjacent to the valve surfaces over which the gases are accelerated to sonic velocity is the best candidate for the TVC system being developed.

2. The basic three-strut-supported centerbody design is satisfactory when used in a valve with no dam.

3. The overall valve design has been proved by testing to be structurally adequate, but the pintle lacks the erosion resistance necessary to meet system specifications.

Recommendations

(U) A recommended approach to solving the pintle erosion problem is as follows:

1. Plans should be formulated for conducting a fundamental investigation into the mechanism of erosion as occurs on pintles of poppet-type hot gas valves.

2. A design study should be conducted parallel with the prime program effort to evaluate (both analytically and experimentally) alternate materials for the pintle.

3. In the unlikely event that the materials problem should prove insurmountable, a method of circumventing the problem by utilizing an adaptive control system to compensate for the erosion of the pintle should be considered.

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IV

TECHNICAL DISCUSSION

A. GENERAL

1. Technical Program Plan

(U) Work was initiated 28 April 1965 by Allegany Ballistics Laboratory, Hercules Powder Company, under Contract AF 04(611)-10748 sponsored by the Air Force Rocket Propulsion Laboratory, Research and Technology Division, Edwards Air Force Base, California. The Technical Program Plan was submitted to the Air Force Project Officer on 17 May 1965. The initial design phase, which included sizing and design of the special testing hardware for the full-scale valve, was completed during the first three-month period. During this second quarter, the full-scale nonactuated valve was tested by static firing to evaluate the specific design; the test results showed that improvements are required. Two additional designs were tested under Hercules sponsorship to evaluate modifications to the valve. The results of these tests, as reported in the following sections, are being further evaluated to determine influence on the design of the prototype valve. All other components for the prototype valve test are being fabricated. Some slippage in the initial milestones is now expected because of the necessary valve modifications.

(U) During this report period the effort was directed to achieve the following technical objectives in Phase A of the program:

    a. Complete the fabrication and test of full-scale non-actuated valves

    b. Evaluate the results of the nonactuated valve tests to arrive at a valve design which will be best for the system test conditions

    c. Complete the fabrication of valve, nozzle, motor, and aft closure for the prototype valve test

2. Phase A - Performance Criteria

(C) The following specifications were set forth by the Air Force in Contract AF 04(611)-10748 for the performance of the actuated lightweight valves tested in Phase A - Component Development and Evaluation:

| Firing duration | 30 seconds for Prototype Valve Test |
| | 60 seconds for Valve Qualification Tests |

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Minimum chamber pressure	600 psia
Actuation response	4 cps (closed-full open-closed)
Modulation capability	from 2% to 100% of valve flow

(U) The valve flow rate must be selected for the vector angle requirement of the demonstration test motor of Phase B.

(C) A high-energy aluminized propellant with a minimum stagnation temperature of 6200°F shall be used.

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B. NONACTUATED VALVE TEST NO. 1 (STATIC FIRING NO. X19051B)

1. Design

(U) The valve shown in Figure 1 was designed to be a nonactuated version of the prototype valve reported in Reference 1 and consisted of five major parts: (1) centerbody with integral support struts and a cavity to house a simulated electrohydraulic actuation mechanism, (2) valve pintle assembly, (3) valve support legs, (4) combined seat and dam assembly, and (5) seat insulator.

(U) The centerbody was supported by three airfoil-shaped struts to minimize disturbance of gas flow. The graphite dam enshrouded the aft cylindrical portion of the centerbody with its enclosed pintle, and served as a flow-directing and flow-straightening device in the gas-accelerating region of the valve. Clearance was provided between each of the circular support legs and the outside diameter of the valve dam to allow for thermal growth of the dam. Stress analysis dictated use of the two-piece dam and seat insert to mitigate the thermal stress effects in this region.

(U) The cylindrical discharge orifice of the valve seat was larger in diameter than the pintle (0.038 inch diametral clearance) to allow for differential thermal expansion of the two parts without binding or seisure occurring in an actuated version of the valve.

(U) The pintle was a composite structure consisting of erosion-resistant graphite, insulation, and actuator-attachment hardware. It was found that a simple open-end cylindrical configuration for the throttling portion of the pintle would have thermal and mechanical stresses of an acceptable level.[1] The heat-treated AHDG graphite shell of the pintle was supported and insulated on its inside diameter by a multi-part structure of asbestos phenolic. The multiplicity of parts was necessary to assemble the pintle in the centerbody of the valve. As shown in Figure 2, the end of the pintle was closed with an asbestos phenolic (RPD-150) plug. Clearance was provided between the graphite shell and the internal phenolic structure to permit escape of the decomposition gases produced by the charring of the insulation, thereby eliminating internal pressure build-up. Additional design details have been previously reported.[1]

(C) The valve was designed to pass 3.5 lb/sec in the full open position at 600 psi. Gas velocity (valve wide open) at various stations in the valve (Figure 3) was controlled by area ratio relationships. These design velocities were chosen consistent with known ablative characteristics of materials used.[1]

(U) As shown in Figure 2, predominant use was made of RPD-130 asbestos phenolic in the valve design. The excellent mechanical and thermal properties of this material enable it to be used as both structural

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and insulative material. Since past Hercules experience with nozzle
inserts indicated heat-treated AHDG graphite to be the most erosion-
resistant graphite with suitable mechanical properties, it was used in
the most critical areas of the valve; namely, the dam, seat, and pintle
shell. For the pressure and velocity environment anticipated for this
valve, erosion rates of about 0.5 mil per second were expected for the
graphite. Specific design details and a comprehensive technical discus-
sion of the compromise between material selection and valve design have
been previously reported.[1]

(U) Although the design of this valve represents a direct
extension of previous successful Hercules work, certain problems were
anticipated for which the solution could be obtained only by actual test
firing. One such unresolved problem was the effect of turbulence created
in the gas stream by the upstream support struts on the pintle erosion.
In addition, since during the nonactuated test the full discharge of the
motor would be passed through the valve, the valve discharge coefficient
would be of critical importance in controlling both chamber pressure and
burning rate of the propellant. Based on past Hercules experience, a
value of 16 percent reduction in discharge coefficient was used in setting
the throat gap for the valve.

2.   Instrumentation

(U) In addition to motor pressure and axial thrust measurement,
fifteen miniature thermocouples (Figure 4) were located at critical positions
within the valve structure. Pairs of thermocouples at known distances from
each other were positioned to provide a means of determining one-dimensional
temperature gradients in the dam and seat. As shown in Figure 4, thermo-
couple pair Nos. 1 and 2 were located in the valve seat, in a plane identi-
cal to that of the upstream support strut. Thermocouple pair Nos. 3 and 4
were located in a circumferential position 180° rotated from pair Nos. 1
and 2 to determine the effect of an upstream strut on the downstream heating
of the valve seat. Thermocouple pairs Nos. 9 and 10 and Nos. 11 and 12
were located in like manner to indicate unsymmetrical heating of the valve
dam. Thermocouple pair Nos. 7 and 8 were situated to permit calculation
of the heat flux to the simulated sonic injection orifice. Thermocouple
No. 13 was located in the pintle assembly to provide a measure of the rate
of transient heating in the longitudinal direction of the graphite pintle
shell, and thermocouple No. 14 was provided to measure the effectiveness
of the pyrolytic graphite wafer in protecting the internal structure of the
pintle. Thermocouple No. 15 was located on the steel support shaft to indi-
cate the effectiveness of the plug internal insulation in protecting the
retaining device. Thermocouples Nos. 1 through 12 were tungsten-tungsten-
26% rhenium. Thermocouples Nos. 13 and 14 were platinum/platinum-10%
rhodium, and thermocouple No. 15 was standard chromel-alumel.

(U) As reported in Reference 1, the original intentions were
to fully instrument the thin graphite shell of the pintle to determine
the complete transient heat transfer characteristics of this critical
part. However, during the actual instrumentation phase it was found that
the small size of the piece to be instrumented precluded installation of
thermocouples directly in the thin graphite shell. The fine (3-mil
diameter) wire used to construct the thermocouples was not sufficiently
ductile to allow manipulation in tightly restricted areas during assembly
of the valve. Special fabrication techniques were used to maintain welded
thermocouple junctions of minimum diameter so that thermal inertia of the
mass would be low and transient response high.

   3.   Test Results (Static Firing No. X19051B)

(U) As discussed in a later section (IV-E), planned test con-
ditions were 640 psi for 25 seconds, using a 48-pound charge of 6300°F
aluminized CMDB propellant.

(U) Ballistic parameters of the firing are shown in Figure 23,
Section IV-E. Maximum chamber pressure of 596 psia was attained approxi-
mately 2-1/2 seconds into the firing, followed by a rapid pressure decay
to approximately 300 psi at 8 seconds. From 8 seconds to 16 seconds,
pressure decay was less rapid, reaching a value of approximately 220 psia
at 16 seconds. From 16 seconds through the remainder of the firing,
pressure remained relatively constant.

(U) Post-firing examination of the nonactuated valve revealed
severe erosion of the valve centerbody As shown in Figure 5, major loss
of material occurred on that part of the valve centerbody contained within
the graphite dam-seat combination. The entire aft section of the valve
centerbody including the pintle assembly was discharged during the course
of the firing. Although the three airfoil-shaped struts were in a region
of nominally low velocity gas, they too experienced abnormal erosion (by
a factor of 3 to 10 times that predicted). Although the outside diameter
of the graphite dam sustained little damage, the internal contour of the
dam was gouged, indicating direct particle impingement. Areas of the dam
and seat which were in the wake of the struts experienced the most severe
erosion. Appraisal of the performance of the graphite pintle was difficult
since this part was ejected during the firing. Examination of the two
pieces of the ejected pintle shell which were recovered showed that they
had experienced severe erosion prior to ejection. This erosion could
account for the rapid decay of chamber pressure.

(U) Analysis of high-speed motion pictures made during the
firing revealed that the bulk of the pintle assembly was ejected approxi-
mately 22 seconds after ignition. From this, it can be surmised that the
rapid loss of pressure at approximately 2-1/2 seconds was due to localized
erosion of graphite material in the flow-throttling region of the pintle.

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(U)   The greater-than-anticipated degree of char and erosion sustained by this valve is graphically illustrated in Figure 6. Char and erosion depths at various stations along the valve centerbody varied from 0.25 inch to 0.79 inch. Measurement of the ejected pintle pieces recovered after the firing indicated that approximately 0.6 inch was eroded from the extended tip of the pintle before ejection of the pintle from the valve. Total erosion in the area of the valve seat was nominal with only approximately 0.008 inch increase in diameter of the simulated sonic injection orifice at a small localized groove.

(U)   Considering the total depth of char and erosion averaged over the burning time, erosion and char rates were greatly in excess of those anticipated. Char and erosion rates for various components of the valve are shown in Figure 6. Values were computed by dividing total char and erosion depth by the burning time (32 seconds). The average chamber pressure was 261 psia.

(U)   Data were obtained with all thermocouples except Nos. 2, 9, 10, 11 and 12 (Figure 4) which either had yielded erratic results or had experienced total loss of continuity. Temperature measurements recorded by thermocouples Nos. 1 through 6 in the vicinity of the valve throat are shown in Figure 7.

(U)   The influence of the upstream struts on heat transfer characteristics at the downstream seat is shown in this figure. The maximum temperature recorded by thermocouple No. 1, which was embedded in an area of the seat lying in the wake of a strut, was approximately 500°F greater than that of thermocouple No. 3 which was embedded in an area not shadowed by a strut. In addition, the heating rates experienced by these two thermocouples, as evidenced by the transient temperature rise, are markedly different, leading one to conclude that the heat transfer coefficient in the wake of a strut exceeded that in an area not in the wake of a strut. The primary cause of the temperature difference noted was apparently turbulence in the boundary layer created by vortices emanating from the upstream strut.

(U)   Figure 8 is indicative of the heating rate experienced by the simulated circular sonic injection orifice. The reason for the apparent decrease in temperature as measured by thermocouple No. 8 at approximately 9 seconds has not been fully established.

(U)   Figure 9 compares the temperature response of thermocouple No. 13 (located in the pintle) with calculated temperature gradients based on two different assumed boundary conditions (Case 1: adiabatic boundary at the graphite-phenolic interface; Case 2: simple contact resistance at the interface). From Figure 9, it appears that the adiabatic boundary assumption is valid. The sudden temperature rise experienced by thermocouple No. 13 at approximately 22 seconds confirms the conclusion that the pintle was ejected from the valve assembly at this time.

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(U)   Test results for thermocouples Nos. 14 and 15 (Figure 10)
demonstrate the effectiveness of the pyrolytic graphite wafers in pro-
tecting the internal structure of the pintle prior to the ejection of
this part.

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FIGURE 1
Prefiring Views of Nonactuated Valve No. 1

G-1298

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RPD-150 (support)

RPD-150 (closure insulator)

Pyrolytic Graphite (washers)

RPD-150 (insulator)

AHDG Graphite (seat)

RPD-150 (centerbody)

17-4 PH (attachment rod)

AHDG Graphite (pintle shell)

RPD-150 (pintle insulation)

AHDG Graphite (dam)
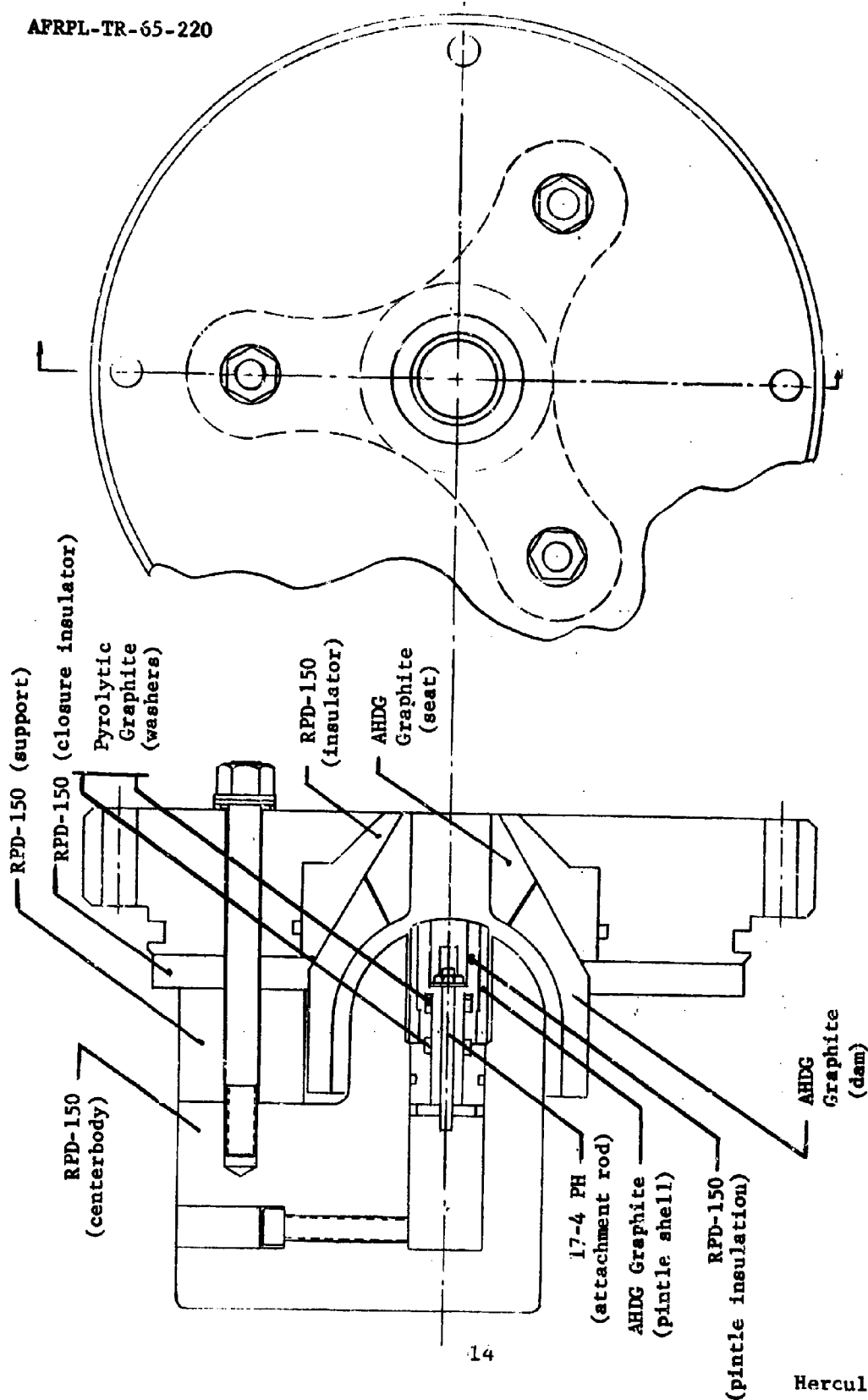
FIGURE 2

Nonactuated Valve #1

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NOTE: Mach Numbers Shown are for Valves Full Open

Sta 5 & 6

Sta 1: M=1.0

Sta 2: M=0.75

Sta 3: M=.49

Sta 6: M = 0.026

Sta 5: M = 0.03

Sta 4: M=0.2
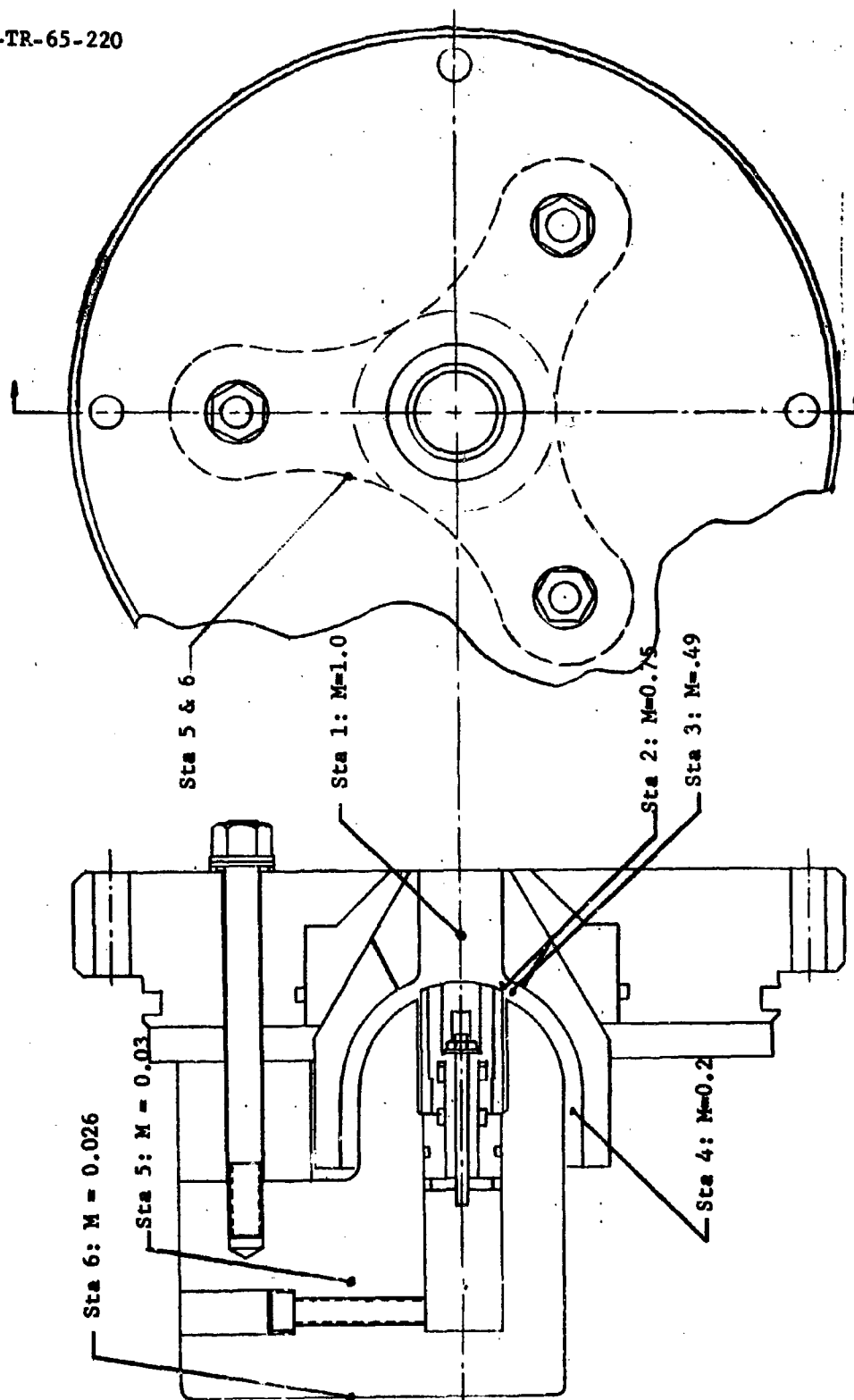
FIGURE 3

Velocity Profile - Nonactuated Valve #1

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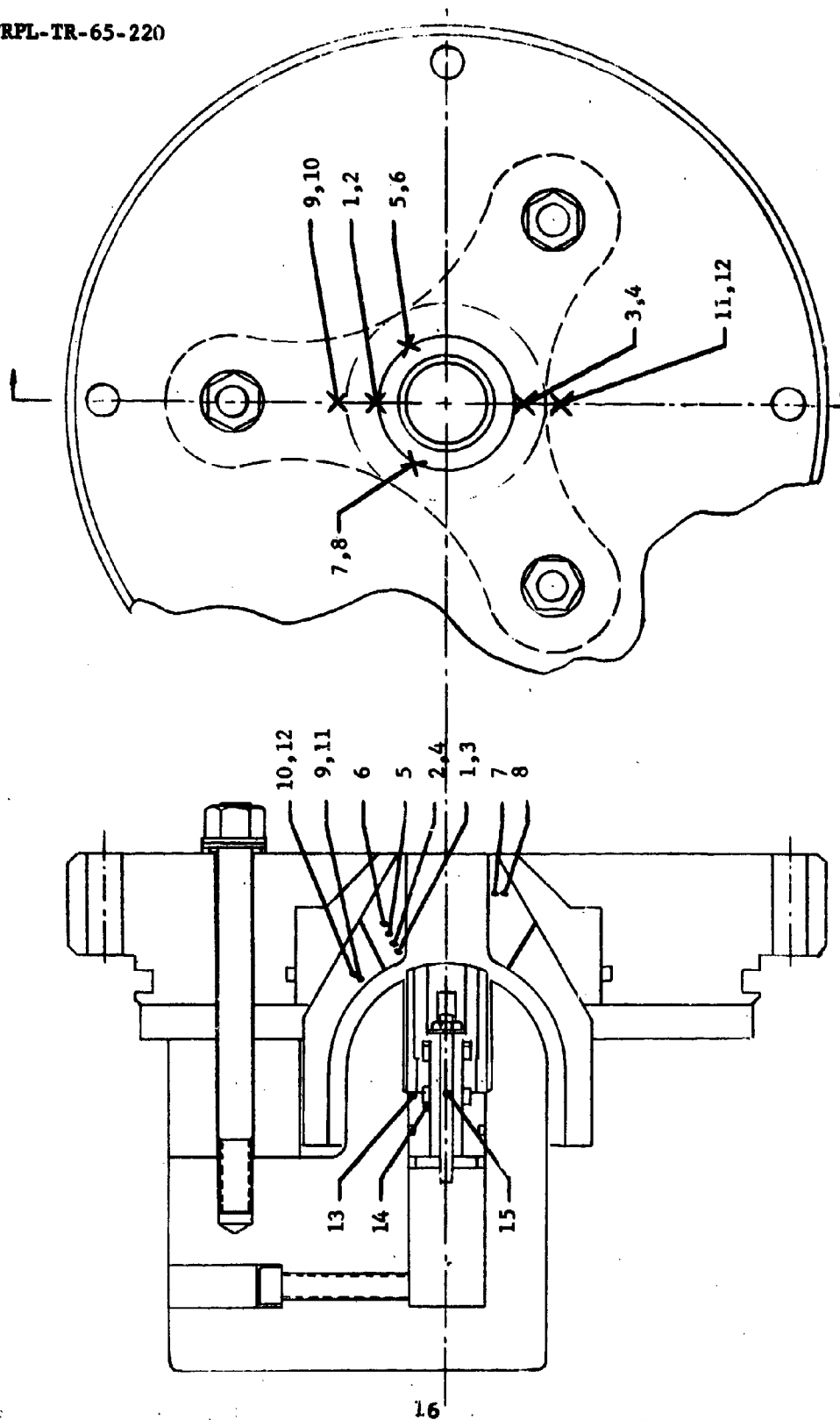
FIGURE 4

Thermocouple Location for First Nonactuated Valve

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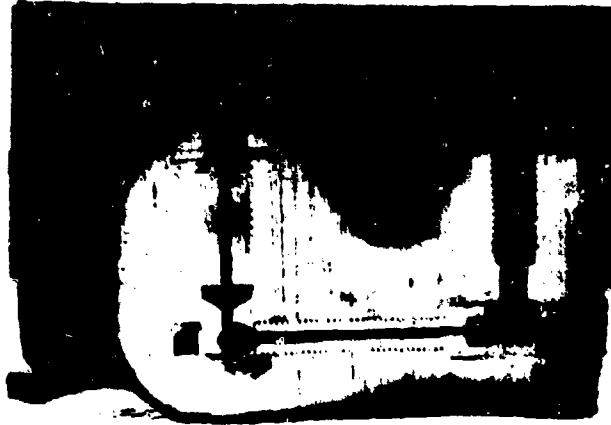
Centerbody Cross Section

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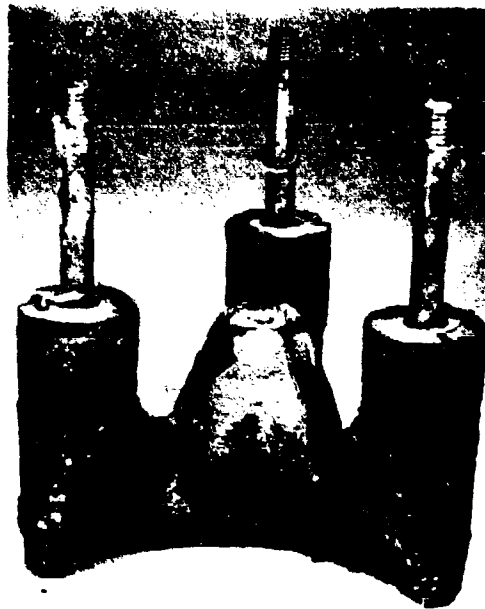
Centerbody

G-1299

FIGURE 5
Postfiring Views of Nonactuated Valve No. 1

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Station	Erosion Rate (mil/sec)*		Char Rate (mil/sec)*	
	Predicted	Actual	Predicted	Actual
A		6.2		9.1
B		9.4		11.6
C		7.8		14.1
D		3.4	4.0	9.1
E		0.9	4.0	4.1
F	10.0	15.6		22.5
G		4.7	6.0	7.8
H	10.0	13.3	11.0	18.0
I		1.6	-	-
J	-	-		-
K	-	-		-
L	0.1	Nil	-	-
M	0.5	27.7**	-	-
N	0.5	21.8**	-	-
O		8.8		10.6
P		6.3		9.4
Q		6.3		9.7
R		2.5		6.3
S		13.1		18.5

*Based on Firing Time of 32 Seconds
**Based on Time of Pintle Ejection at 22 Seconds

----Final Configuration (virgin material)

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FIGURE 6

Post Firing Condition - Nonactuated Valve #1

Section X-X

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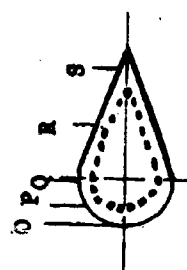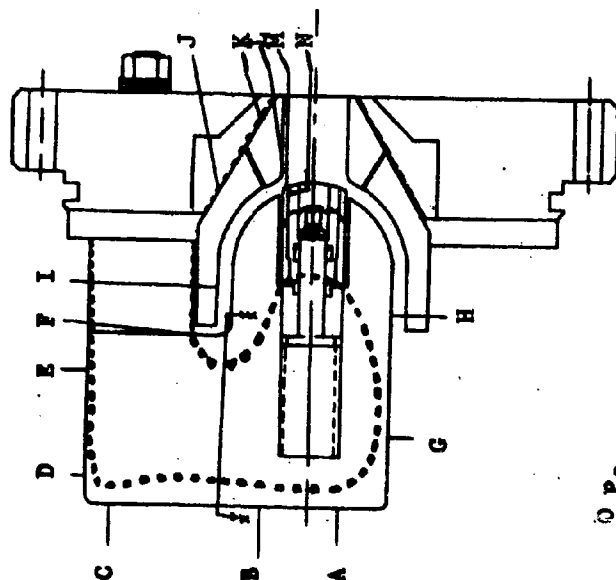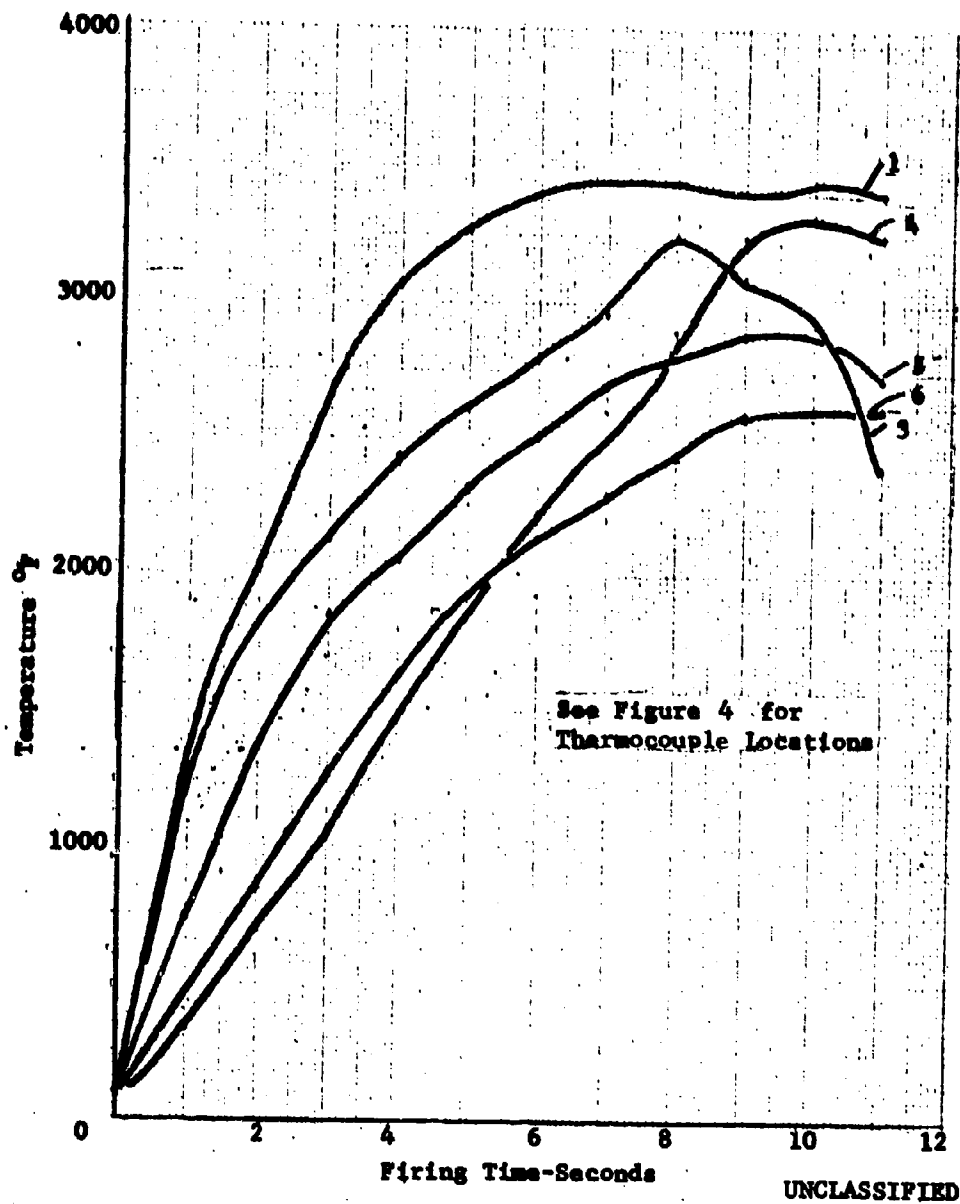
FIGURE 7

Throat Temperatures
Nonactuated Valve No. 1

19
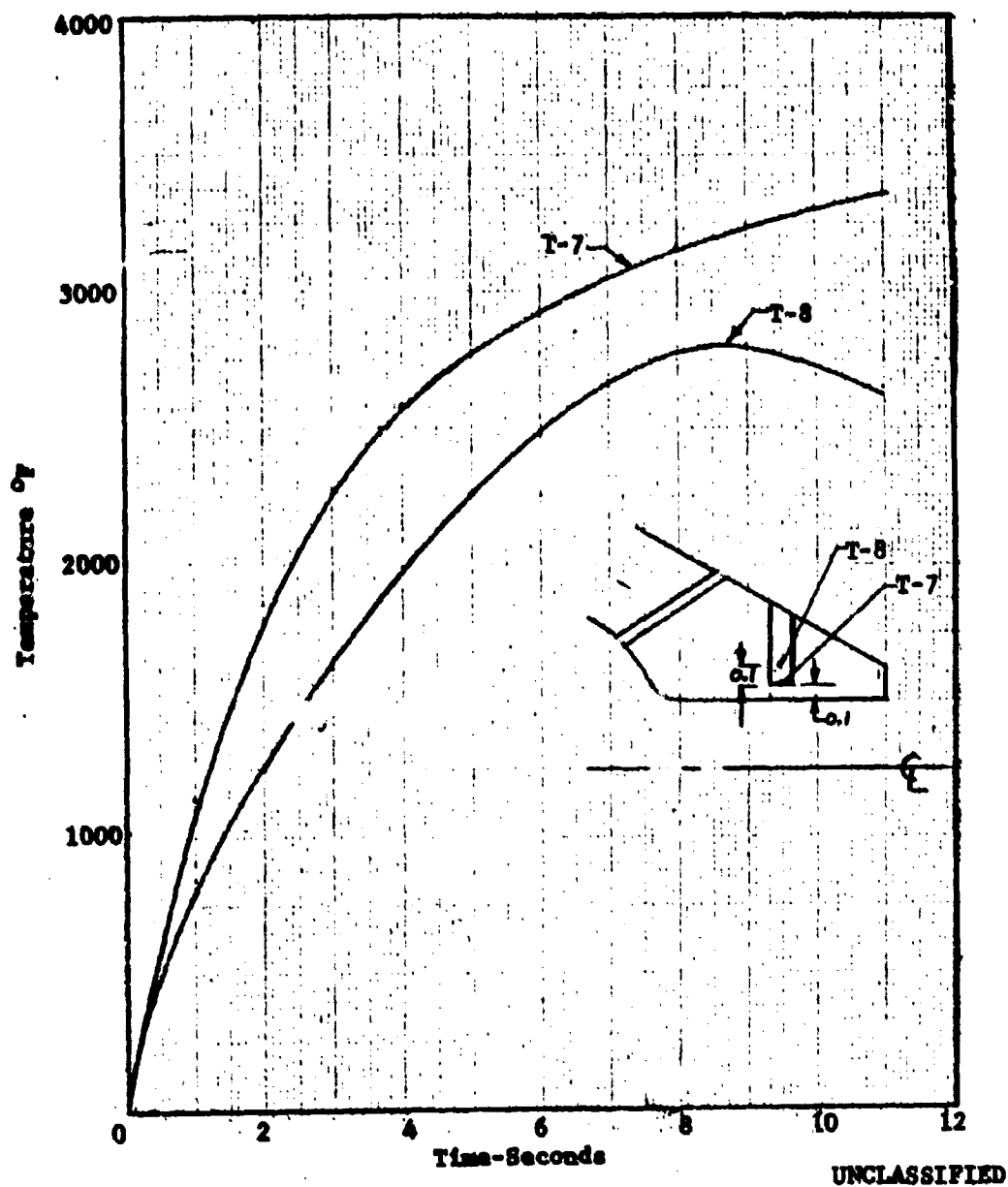
FIGURE 8

Seat Temperatures
Nonactuated Valve No. 1

20

T_W = Calculated Temperature (with noninsulated graphite-phenolic interface) of the Pintle Forward End

T_{13} = Measured Temperature of Pintle Forward End during Test of A.F. #1 Valve

T_I = Calculated Temperature (with insulated graphite-phenolic interface) of Pintle Forward End
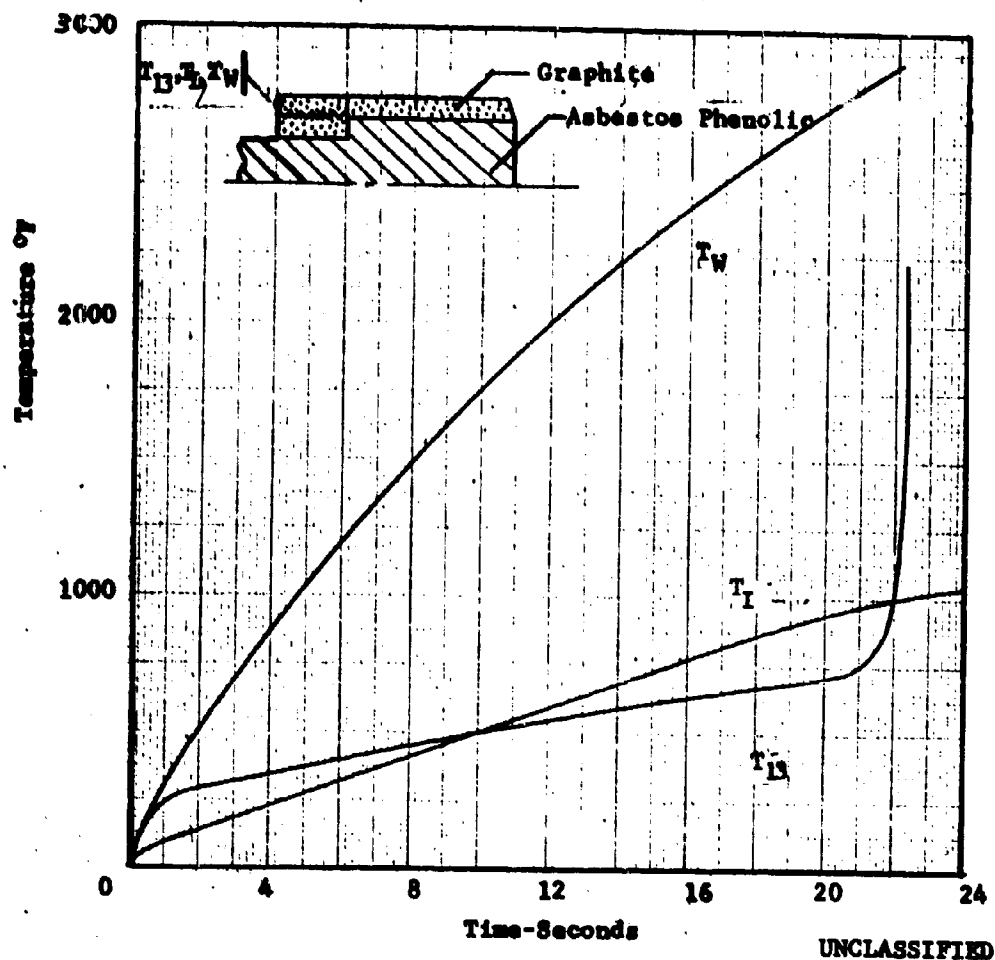
FIGURE 9

Analytical vs. Experimental Pintle Temperatures

21
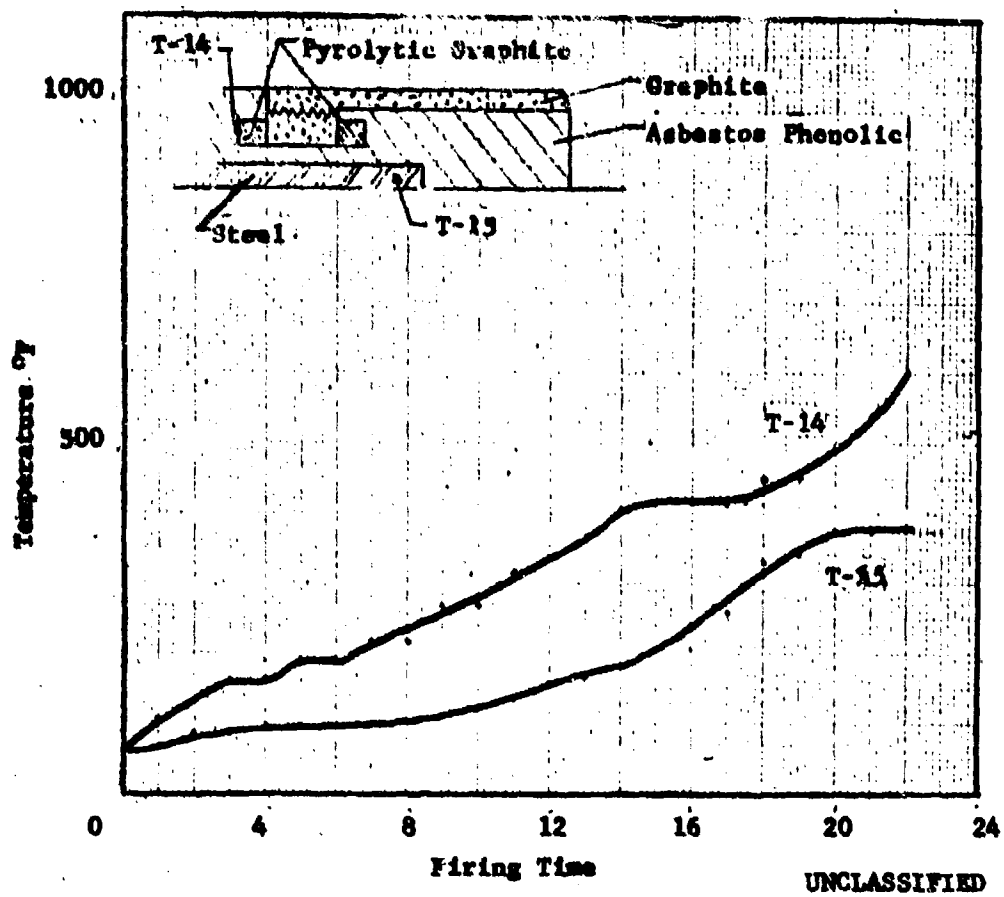
FIGURE 10

Pintle Temperatures
Nonactuated Valve No. 1

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C. NONACTUATED VALVE TEST NO. 2 (STATIC FIRING NO. X19109B)

1. **Design**

(U) As a result of the severe erosion experienced by the first nonactuated valve, the design was modified to the configuration shown in Figure 11. The two major changes made were (1) elimination of the graphite dam which enshrouded the aft cylindrical portion of the centerbody of non-actuated valve No. 1, and (2) modification of the approach angle to the valve seat. By eliminating the dam, velocity of the gas stream along and adjacent to the valve centerbody could be maintained at a very low Mach number ($M \sim 0.03$). The key objective of this redesign was to minimize the path length adjacent to the valve surfaces over which gases are accelerated to sonic velocity.

(U) While the basic centerbody configuration of nonactuated valve No. 1 was maintained in this valve design, minor changes were made in the support strut configuration. The width of the support struts was decreased and their overall length was increased to improve aerodynamic design. Based on the char and erosion data for the struts used in non-actuated valve No. 1, the revised strut configuration would provide adequate insulative protection (over a 60-second or greater firing time) for hydraulic lines which would pass through the struts in the actuated version of the valve.

(U) As in the first nonactuated valve design, the cylindrical discharge orifice of the valve seat was larger in diameter than the pintle (0.038 in. diametral clearance) to allow for differential thermal expansion of the two parts without binding or seizure occurring in an actuated version of the valve. The basic pintle design was not changed.

(C) The valve was designed to pass 3.5 lb/sec propellant gas while in a full open position at 600 psi chamber pressure.

(U) No changes in material were made since it was evident from results of testing that the problem with the first nonactuated valve was primarily one of gas flow distribution rather than material properties.

2. **Instrumentation**

(U) In addition to motor pressure and axial thrust measurement, three miniature thermocouples were installed in the same pintle locations as in the first nonactuated valve. The purpose of these thermocouples has been previously discussed in Section IV-B. Two of the miniature thermocouples were constructed of platinum/platinum-10% rhodium and the remaining thermocouple was standard chromel-alumel.

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3. **Test Results**

(U) As discussed later (Section IV-E), planned test conditions were 660 psi for 6.0 seconds using a 12-pound charge of 6300°F aluminized CMDB propellant. The reduced firing time of 6 seconds was considered adequate to achieve the primary test objective which was to determine the improvement in valve design to be gained by eliminating the dam.

(U) Ballistic parameters of the firing are shown in Figure 24, Section IV-E. Maximum chamber pressure of 858 psia, attained approximately 1 second into the firing, was followed by a uniform pressure decay to approximately 200 psia at 6 seconds. The chamber pressure decay was a direct result of pintle and seat erosion in the throttling region of the valve.

(U) Post-firing examination of the valve revealed that char and erosion depths were as predicted. Char and erosion rates (calculated by dividing total depth of char and erosion by a firing time of 6.5 seconds) are shown in Figure 12.

(U) With the exception of the pintle, the post-firing condition of the valve was satisfactory (Figure 12). The exposed end of the heat-treated AHDG graphite pintle shell eroded back in length at a calculated rate of 37 mils/sec on the outside diameter and 17.9 mils/sec on the inside diameter. While these rates are consistent with those measured for the pintle in the first nonactuated valve, they represent a two-order of magnitude increase over predicted erosion rates for this material. As shown in the post-firing photograph (Figure 13), the phenolic plug in the end of the pintle was eroded back to a greater depth than that of the surrounding graphite shell. This increase in erosion may be accounted for by turbulence and/or back flow created as the result of shock wave interaction in the supersonic region of the valve. Erosion of the valve seat was negligible.

(U) Data were obtained with all three thermocouples although their initial response was erratic (Figure 14). Referring to Figure 14, the sudden increase in temperature, as measured by thermocouple No. 15, was caused by direct exposure to flame temperature following rapid erosion of the asbestos phenolic pintle closure plug. An exploded post-firing view of the pintle assembly is shown in Figure 15.

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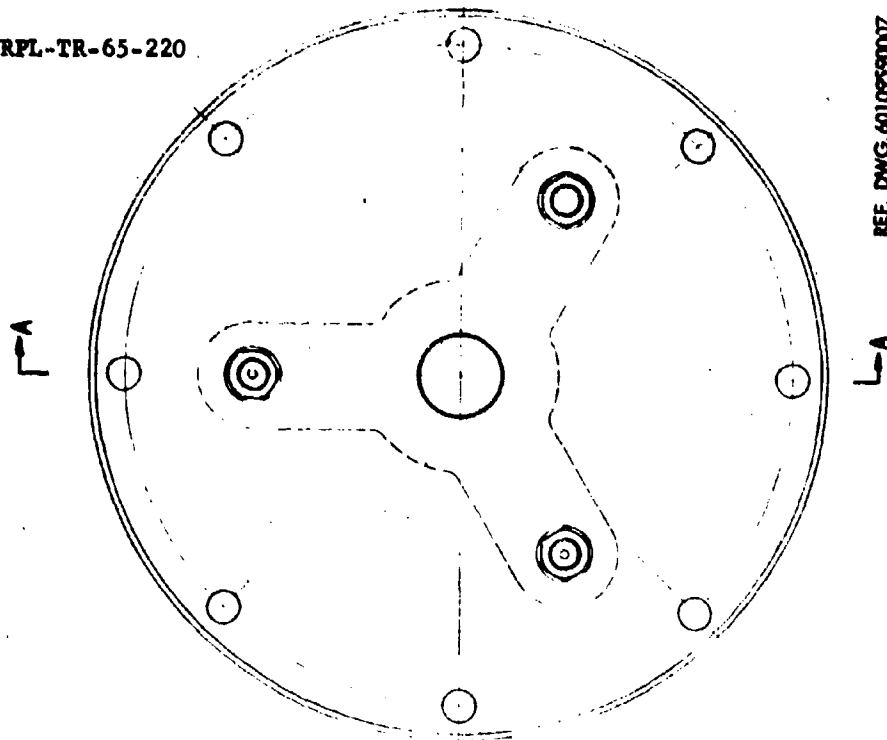
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INSULATOR

PINTLE

SEAT

STEEL CLOSURE

FASTENING ROD
(THREE)

SUPPORT
(THREE)

CENTERBODY
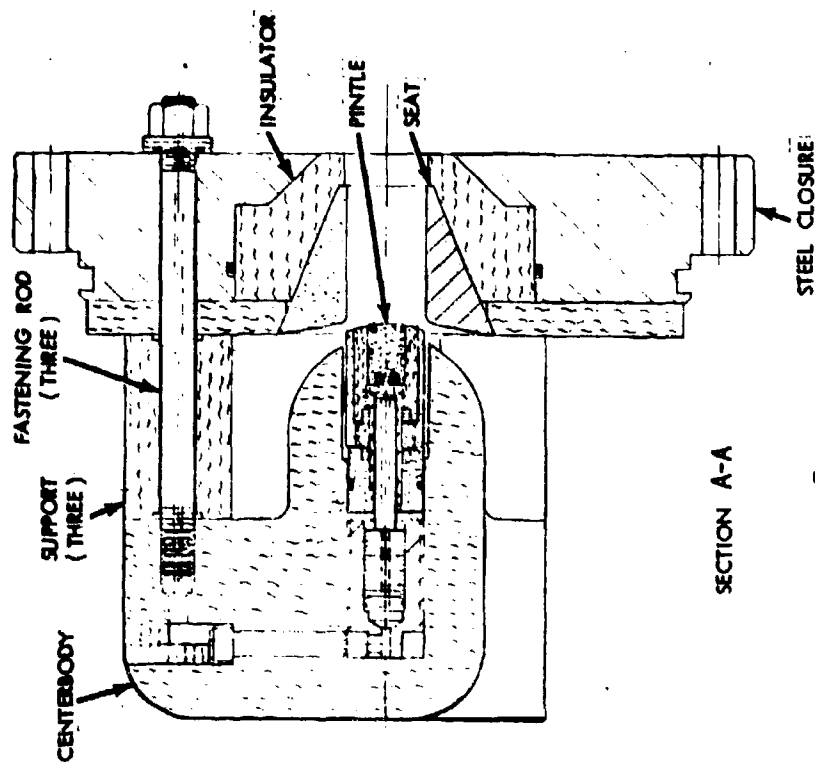
SECTION A-A

FIGURE 11

Assembly Drawing of Nonactuated Valve No. 2

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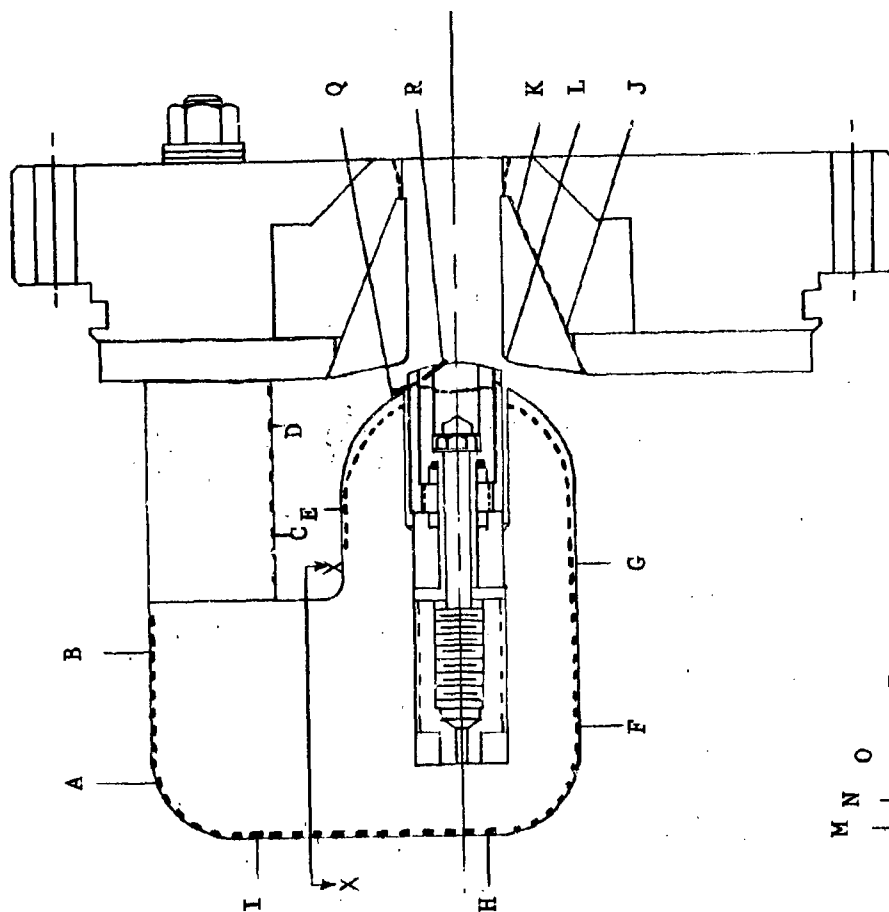
Section	Erosion Rate* mil/sec	Char Rate* mil/sec
A	Nil	10.8
B	Nil	9.2
C	1.8	12.5
D	1.8	14.1
E	2.2	14.5
F	Nil	10.8
G	2.2	14.5
H	Nil	10.8
I	Nil	9.2
J	0	1.5
K	0	6.2
L	Nil	-
M	Nil	10.2
N	Nil	11.0
O	2.6	12.6
P	3.0	13.8
Q	37.0	-
R	17.9	-

*Based on Firing Time of 6.5 Seconds

---- Final Configuration (virgin material)

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FIGURE 12

Section X-X

Post Firing Condition - Nonactuated Valve #2

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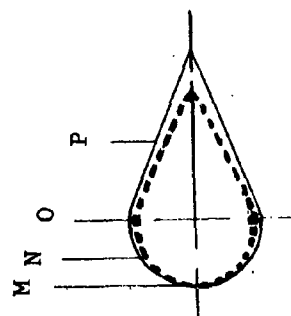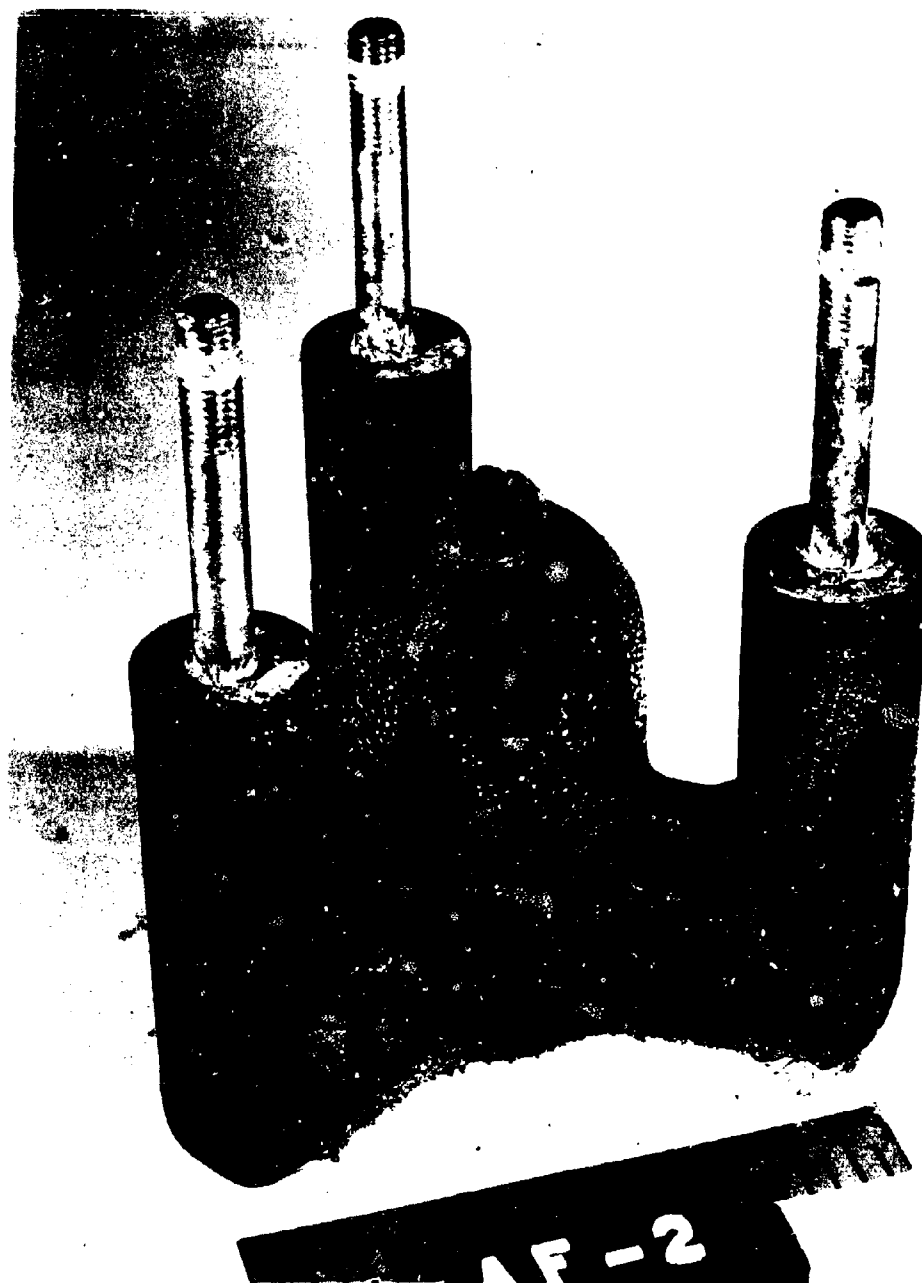
FIGURE 13   G-1296
Postfiring View of Nonactuated Valve No. 2

27
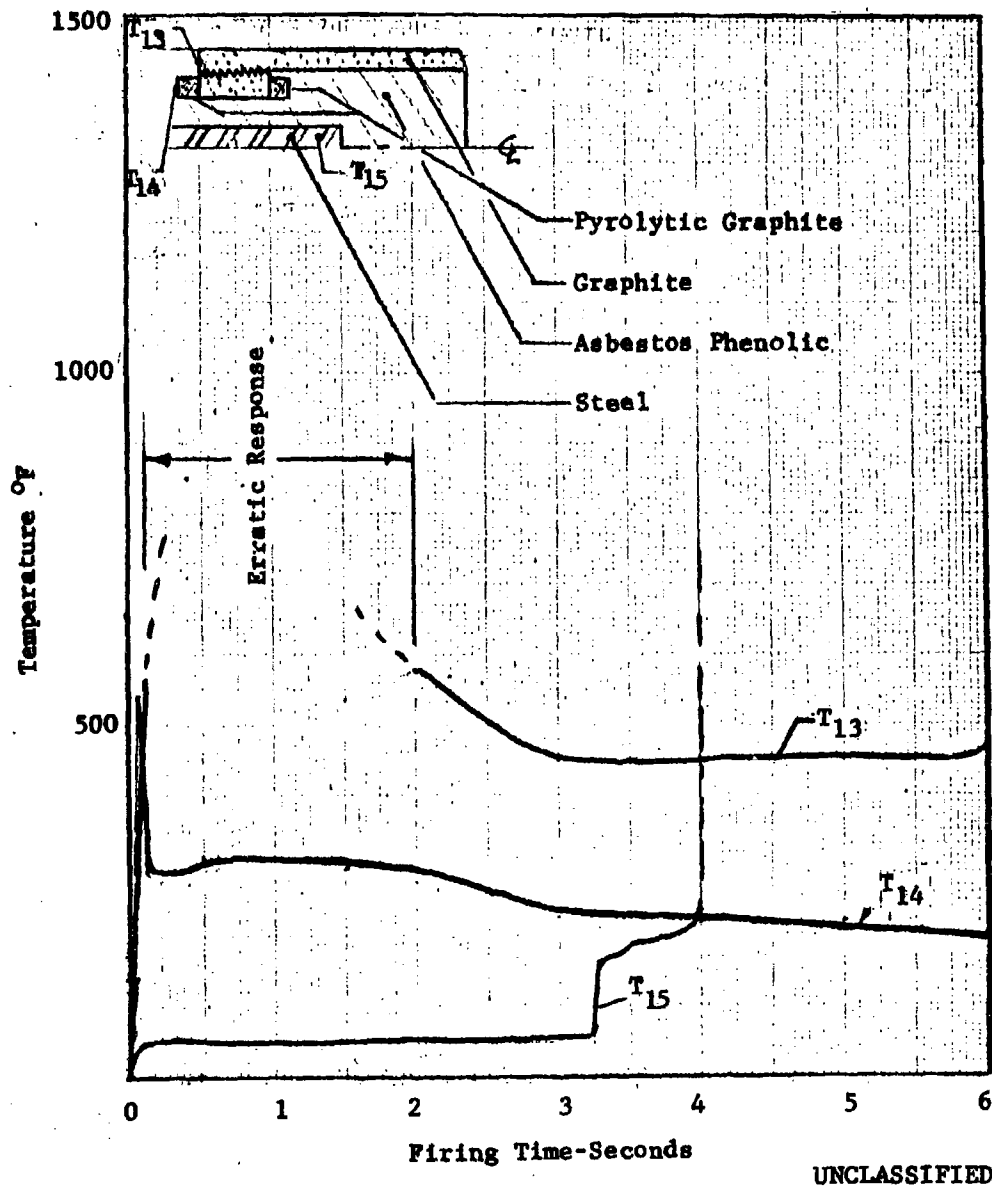
FIGURE 14

Pintle Temperatures - Second Nonactuated Valve

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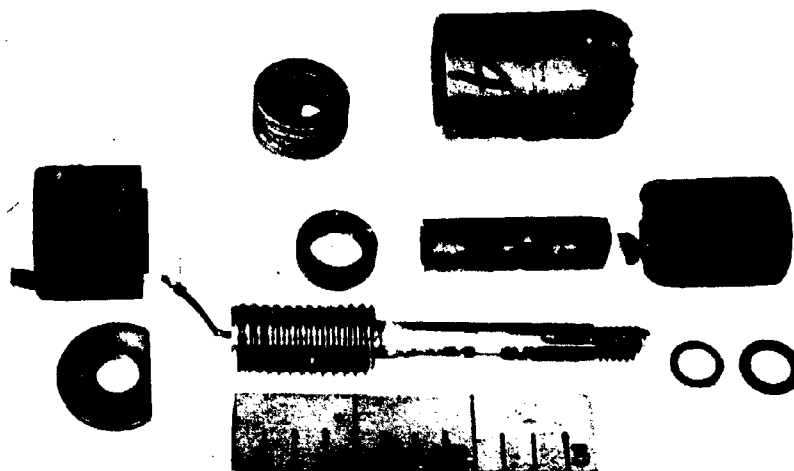
FIGURE 15   G-1295
Postfiring View of the Pintle Assembly in Nonactuated Valve No. 2

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D. **NONACTUATED VALVE TEST NO. 3 (STATIC FIRING NO. X19144B)**

(U) The third nonactuated valve to be designed and tested was modeled
after earlier successful in-line configurations; i.e., full dam and two struts.
The "in-line" valves have experienced less pintle erosion, possibly because
of the flow-straightening effect of an enclosed flow channel.

1. Design

(U) The inside contour of the dam was tapered to maintain constant
Mach number in the gas stream around the centerbody. The centerbody was sup-
ported with two airfoil-shaped struts, 180° apart. The two struts were of
unequal length, as shown in Figure 16, to evaluate the effect of strut length
and position on flow pattern. The struts were machined to fit the tapered
contour of the inside surface of the dam as shown on the assembly drawing
(Figure 17). The centerbody, the same size as used in the other two valves,
was bolted and pinned to the dam through each strut. A view of the assembly
is shown in Figure 16. The major diameter of the conical (approximately
3°) dam was set to maintain the same cross-sectional flow area at the widest
portion of the strut as in the strut-free passage. Both the centerbody and
the full length dam were constructed of RPD-150 asbestos phenolic.

(U) The pintle used in this valve was of the same design as those
of the first and second nonactuated valves except for modification of the end
closure plug to provide more positive retention. The seat of the third non-
actuated valve was fabricated from MHLM-85 graphite and extended around the
end of the centerbody, blending into the taper of the dam. The modified
EM-26 steel closure was insulated from the graphite seat with RPD-150 in a
manner similar to that of the other two nonactuated valves.

2. Instrumentation

(U) Two thermocouples were incorporated in this test. One of the
thermocouples was located in the pintle at the same position as thermocouple
No. 13 in the first valve test (Figure 9, Section IV-B). The other thermo-
couple was positioned in the steel support shaft in a location similar to
that of thermocouple No. 15 in the other nonactuated valve tests. Chamber
pressure and axial thrust were measured for the duration of the firing.

3. Test Results

(U) Based on the pressure data obtained from the first valve firing,
the throat area was set approximately the same as for the first valve and a
maximum chamber pressure of 660 psi was predicted. The 12-pound charge was
ignited and pressure rose to approximately 500 psia in 0.2 second, as shown
in Figure 25, Section IV-E. The pressure continued progressively for about
2 seconds and leveled off at 620 psia. Approximately 3.25 seconds after
ignition, pressure started to decay, reaching 520 psia at 5.25 seconds, and

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then dropping to 180 psia within 1 second.

(U) Examination of the third nonactuated valve parts showed that the erosion of the centerbody was slightly greater than that of the second valve, especially at the end next to the pintle where 0.1 inch was removed. Erosion along the internal surface of the dam was uniform except in the area of the support struts where it was slightly greater. Erosion of the graphite seat was unmeasurable. Examination of the AHDG-graphite pintle sleeve revealed slightly less erosion and grooving than that experienced by the second valve pintle (see Figure 18). The sleeve was grooved directly behind both struts; the short strut caused a slightly wider groove, indicating that short struts are more detrimental than the longer struts in this design. Figure 19 indicates the lines of erosion and char of the valve assembly and gives the rates at various locations. The phenolic insert of the pintle was eroded more than the end of the graphite sleeve, but the pintle attachment nut was not exposed to the flame as in the other valve tests.

(U) A plot of the response of the thermocouples (see Figure 20) in the pintle revealed that the temperature in the graphite sleeve rose gradually to approximately $800^\circ F$ in 6 seconds. The thermocouple in the steel shaft showed no change in temperature.

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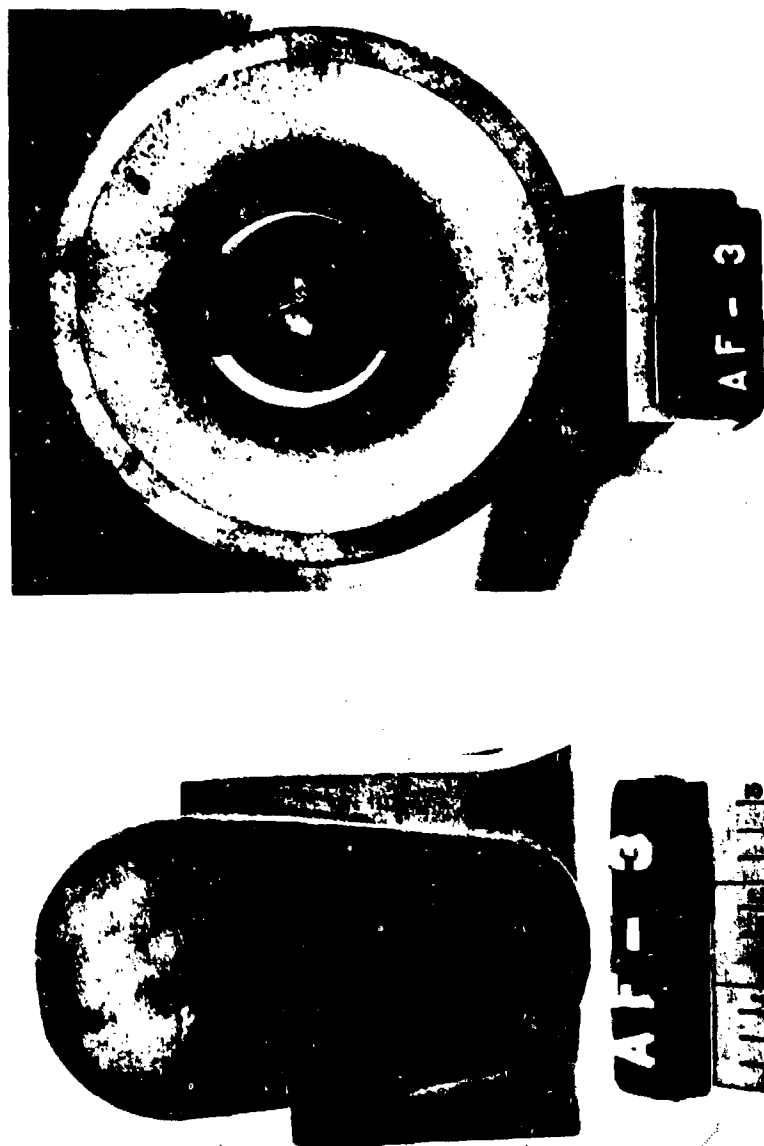
G-1294

Assembly
(Leading End View)

Centerbody
(Note Different Strut Length)

FIGURE 16
Prefiring Views of Nonactuated Valve No. 3

STEEL CLOSURE

SEAT

INSULATOR

PINTLE

FASTENING ROD (THREE)

SECTION A-A

CENTERBODY

DAM
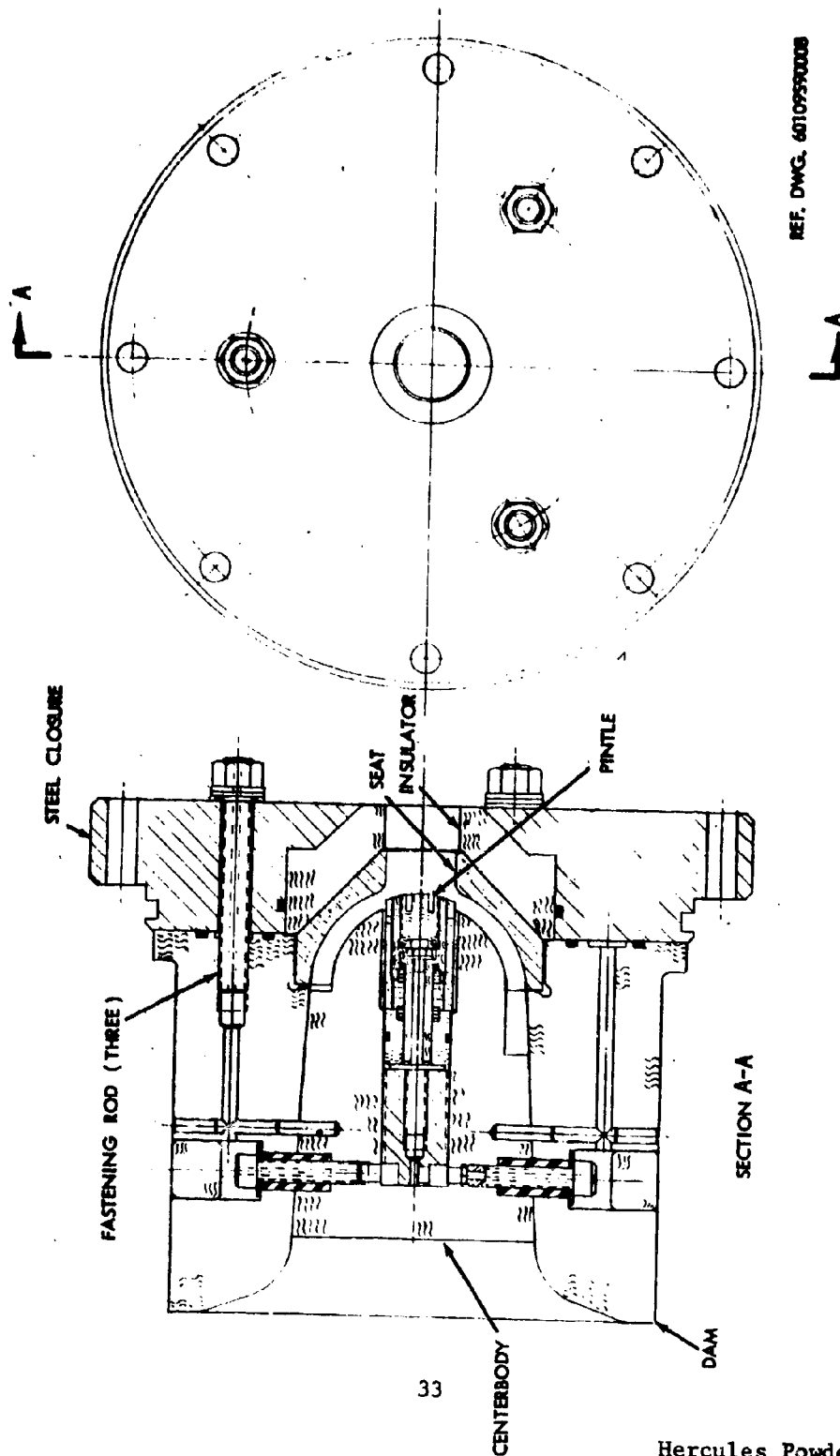
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FIGURE 17

Assembly Drawing of Nonactuated Valve No. 3

33
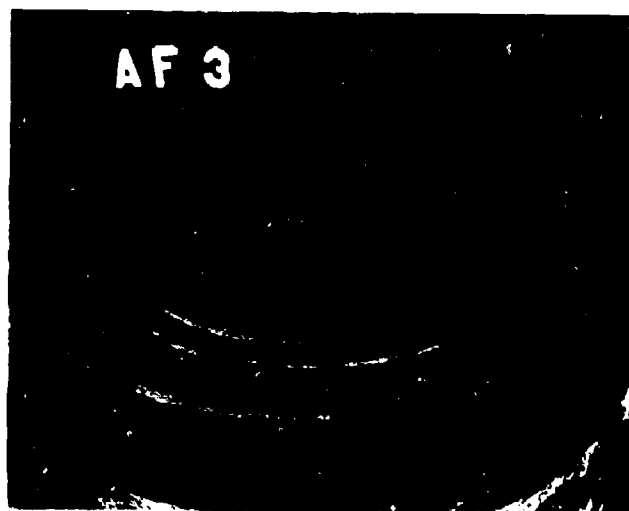
Assembly
(Aft End View)

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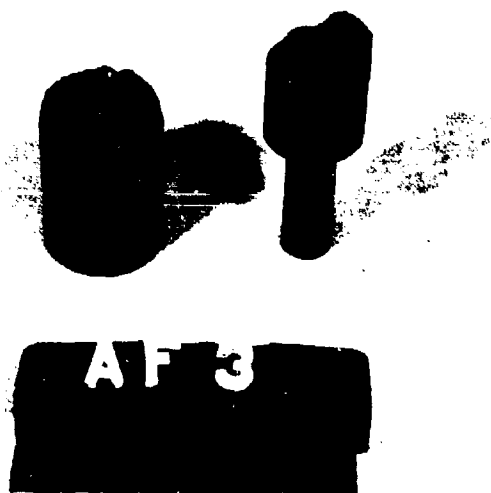
Pintle   G-1297

FIGURE 18
Postfiring Views of Nonactuated Valve No. 3

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Section	Erosion Rate* mil/sec	Char Rate* mil/sec
A	12.0	20.8
B	5.4	17.0
C	12.0	20.0
D	-	11.2
E	Nil	-
F	3.0	4.6
G	7.45	19.6
H	48.0	6.4
I	3.0	11.0
J	10.6	26.1
K	10.0	8.0
L	48.0	-
M	4.8	-

*Based on Firing Time of 6.25 Seconds

--Final Configuration (virgin material)

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Section X-X

Section Y-Y
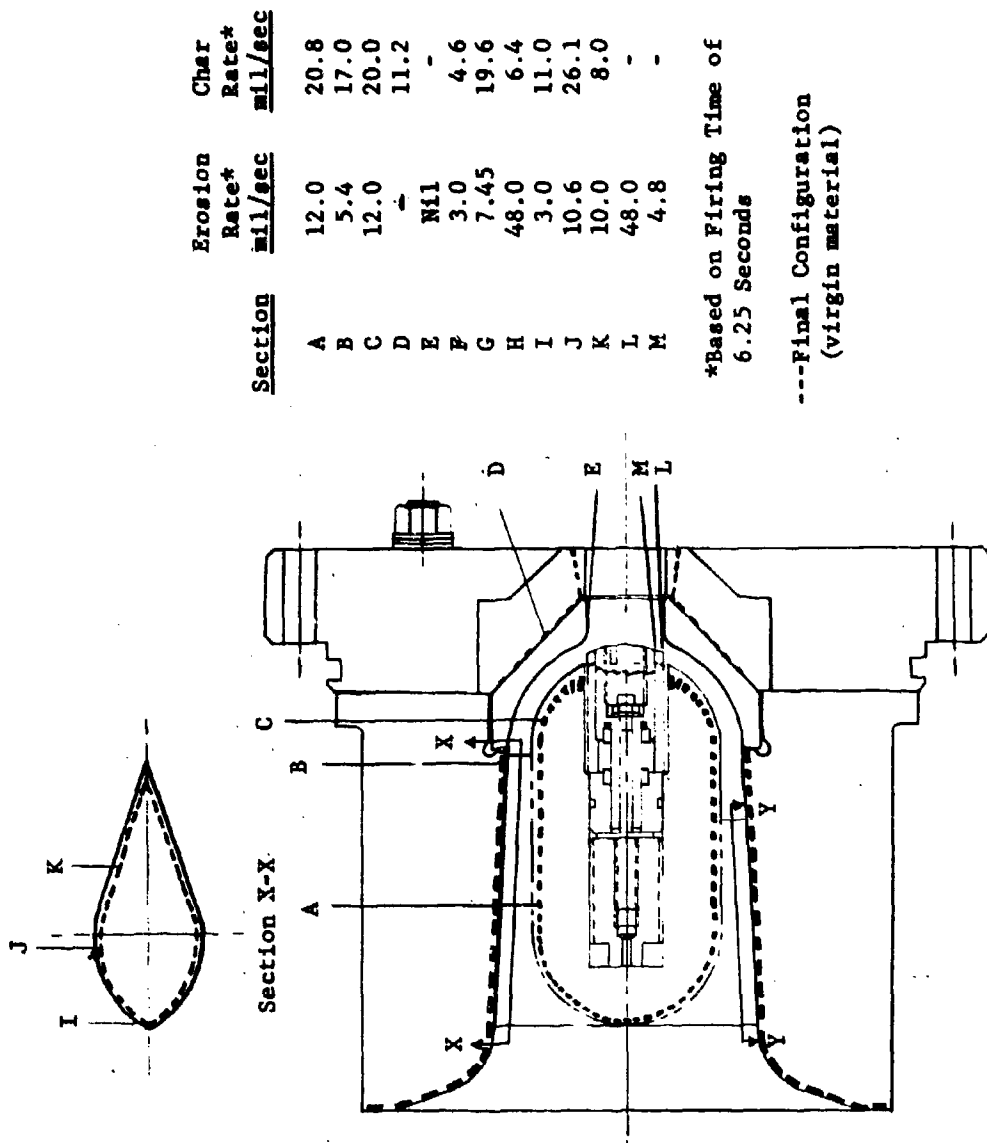
FIGURE 19

Post Firing Condition - Nonactuated Valve #3

35

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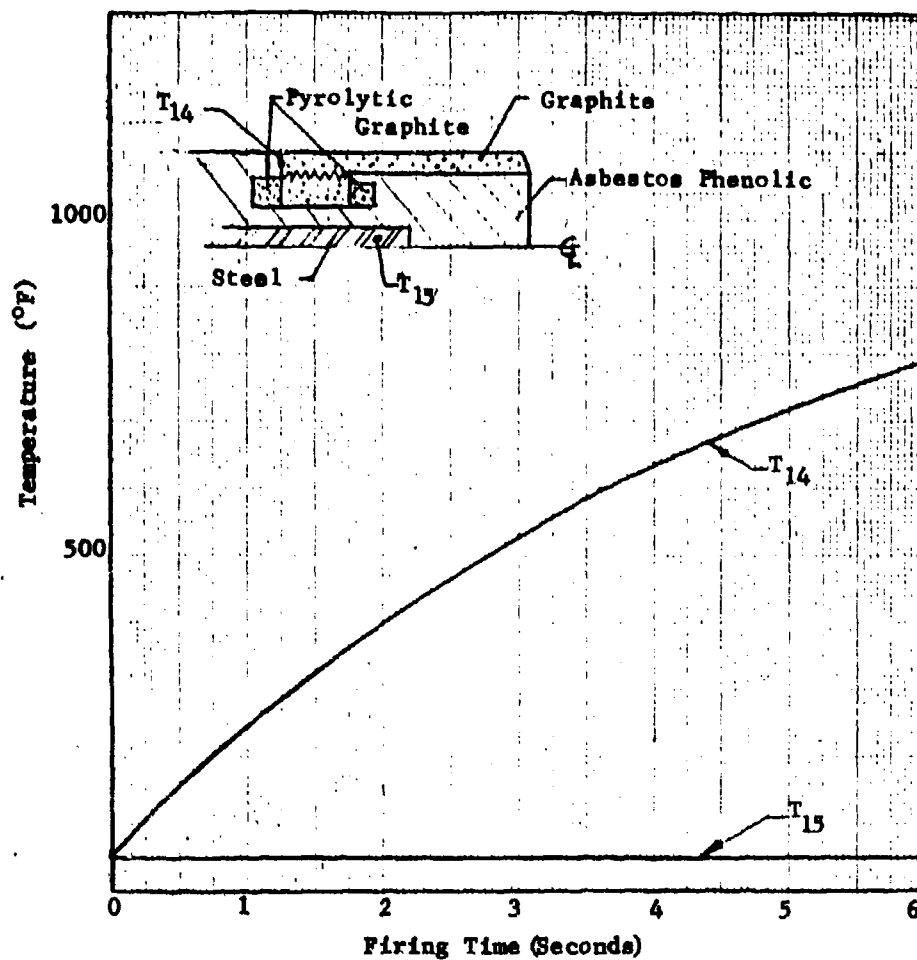
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FIGURE 20

Third Nonactuated Valve Pintle Temperatures

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E.   TEST MOTOR FOR NONACTUATED VALVE TESTS

(U) The three nonactuated valve designs were evaluated in the EM-26 test motor as shown in Figure 21. The main differences in test motors of the three nonactuated valve tests are listed in Table I.

(U) The EM-26 test motor uses a heavyweight steel chamber capable of withstanding internal pressures in excess of 2000 psi and insulated with a 1/4-inch-thick sleeve of asbestos phenolic (A-A Spauldite). The chamber has been designed to contain a propellant charge with an outside diameter of 8 inches and lengths up to 50 inches.

(U) The propellant composition for the nonactuated valve tests was DDP-75, an aluminized composite-modified, double-base propellant. Figure 22 shows the predicted burning rate curve based on 10-pound charge test results for propellant of this type.

(U) The 8-inch-diameter solid propellant charges were inhibited with 1/4-inch-thick cellulose acetate on the circumference and forward end to confine the burning to the aft end surface, thus maintaining a constant burning surface. The end-burning propellant charges were sized in length for an average burning rate of 0.6 inch per second at a chamber pressure of 600 psia; the first test for 25 seconds and the other two for 6 seconds each. The propellant weights used were 48 pounds in the first test and 12 pounds in each of the other two tests.

(U) Satisfactory ignition was obtained in all three tests by the use of a 50-gram bag of $BKNO_3$ pellets. The average burning rate versus average pressure of each firing is plotted on the burning rate curve shown as Figure 22. The average burning rate of each firing agrees within 5.4% with the predicted rate.

(U) The maximum predicted pressure for the first test was 700 psi. For the two shorter firings the maximum predicted pressure was 660 psi immediately after ignition, followed by a decay to 600 psi over the duration of the firing and finally terminating in a rapid drop in pressure at the end of the firing.

(U) The resulting mass flow rate of discharge over the duration of each firing has been determined by the expression:

$$\dot{m} = S r \rho$$

where

$\dot{m}$ = mass flow rate

S = propellant burning surface area (50.27 in.^{2})

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r = propellant burning rate (from Figure 22)

ρ = propellant density (From Figure 22, 0.6212 lb/in.^{3})

Since the average burning rate versus pressure of the three firings agrees with the predicted, the burning rate curve in Figure 22 was used to determine the burning rate at various pressures.

1. First Valve Test

(U) To obtain a chamber pressure of 600 psia, the theoretical throat area is 0.488 in.^{2} This value was determined by the following relationships:

$$\dot{m} = PC_D A_t$$

$$\dot{m} = Sr\rho$$

$$r = cP^n$$

$$PC_D A_t = Sr\rho = S_c P^n \rho$$

$$A_t = \frac{Sc\rho}{C_D P^{1-n}}$$

where

S (burning surface)	$= \frac{\pi}{4}(D^2) = \frac{\pi}{4}(8)^2 = 50.27$ in.^{2}
r (burning rate)	$= 0.6$ in./sec (from Figure 22 for P = 600 psia
c (burning rate constant)	$= 0.0639$ (calculated for 600 psia)
n (burning rate constant)	$= 0.35$ (experimental)
P (chamber pressure)	$= 600$ psia (minimum)
ρ (propellant density)	$= 0.06212$ lb/in.^{3} (experimental)
C_D (discharge coefficient)	$= 0.0064$ (experimental)

Therefore:

$$A_t = 0.488 \text{ in.}^2 \text{ (theoretical)}$$

(U) Data of earlier hot gas valves of similar design indicate a discharge efficiency of 84%, giving a smaller effective throat. The predicted component erosion (seat and pintle) increases the area by 0.042 in.^{2} during the

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firing. Therefore, the initial measured throat area was adjusted to account for both discharge efficiency and erosion for a final pressure of 600 psi. The initial throat area was

$$A_t = \frac{0.458}{0.84} - 0.042 = 0.539 \text{ in.}^2$$

(U) The peak chamber pressure of 595 psia was achieved in approximately 2.5 seconds in the first nonactuated valve test (see Figure 23). The pressure then dropped rapidly, apparently due to erosion of the valve components.

(U) As a result of initial low pressure in the first valve test, the C_D correction of 84% seemed to be in error. Loss of the pintle and grooving of the seat precluded ballistic evaluation.

(U) The calculated resulting mass rate of discharge and the thrust and pressure time curve are plotted in Figure 23. A maximum flow rate through the first valve during the firing was approximately 1.8 lb/sec. and the average flow rate for the duration of the firing was approximately 1.5 lb/sec.

2. Second Valve Test

(U) For the second nonactuated valve the C_D correction was changed from 84% to 90% to correct the initial low pressure condition found in the first valve test. The measured throat area for this valve was 0.489 in.^{2} The peak chamber pressure in this test, which occurred at approximately 1 second, was 193 psia above the predicted (660 psia) and then dropped to 200 psia in 5 seconds. See Figure 24 for the pressure, thrust, and mass flow rate versus time curves.

(U) The mass flow rate was calculated to be 2.15 lb/sec at a chamber pressure of 858 psia (maximum) and decreased to approximately 1.0 lb/sec at 6.5 seconds of burning time, the average being about 1.7 lb/sec.

3. Third Valve Test

(U) Because the chamber pressure in the second test exceeded that predicted and because the third valve design (full dam) more closely resembled earlier in-line valve designs tested at HPC/ABL, the discharge coefficient for the third valve design was assumed to be the same as in past testing (84%) and the throat area used was the same as for the first valve test.

(U) The pressure trace for the third valve design test, as shown on Figure 25, rose to approximately 500 psia in 0.2 second after ignition. The trace was progressive for approximately 2 seconds, leveling off at nearly 620 psia. Pressure started to slowly decline about 3.25 seconds after ignition.

The pressure was approximately 520 psia at 5.25 seconds of firing, at which time the pressure dropped to 180 psia at 6.25 seconds after ignition.

(U)   The average mass flow rate was calculated to be 1.84 lb/sec and the maximum rate, 1.90 lb/sec.

TABLE I

Summary of Nonactuated Valve Tests

	Valve		Propellant			Test Plan			Test Results		
Design	Throat Setting (in.^{2})	C_D Efficiency (%)	Weight (lb.)	Length (in.)	Diameter (in.)	Max. Pressure (psia)	Avg. Pressure (psia)	Firing Time (sec.)	Max. Pressure (psia)	Avg. Pressure (psia)	Firing Time (sec.)
Half-Dam	0.539	84	48.16	15.00	8	700	650	25	595	261	32.00
No-Dam	0.489	90	11.39	3.63	8	660	630	6	853	543	6.50
Full-Dam	0.539	84	11.59	3.67	8	660	630	6	618	522	6.25

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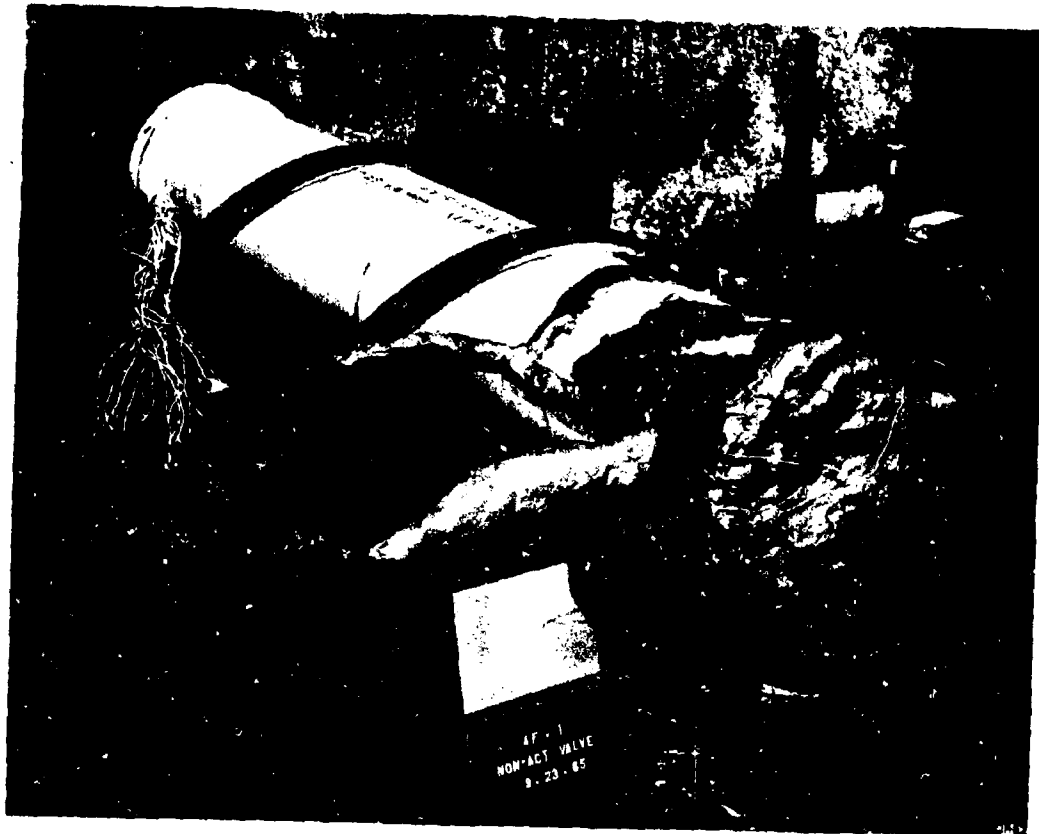
FIGURE 21
Prefiring View of EM-26 Motor in Test Bay

G.-1300

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—— Predicted
⊙ Actual Average of Nonactuated Valve Test
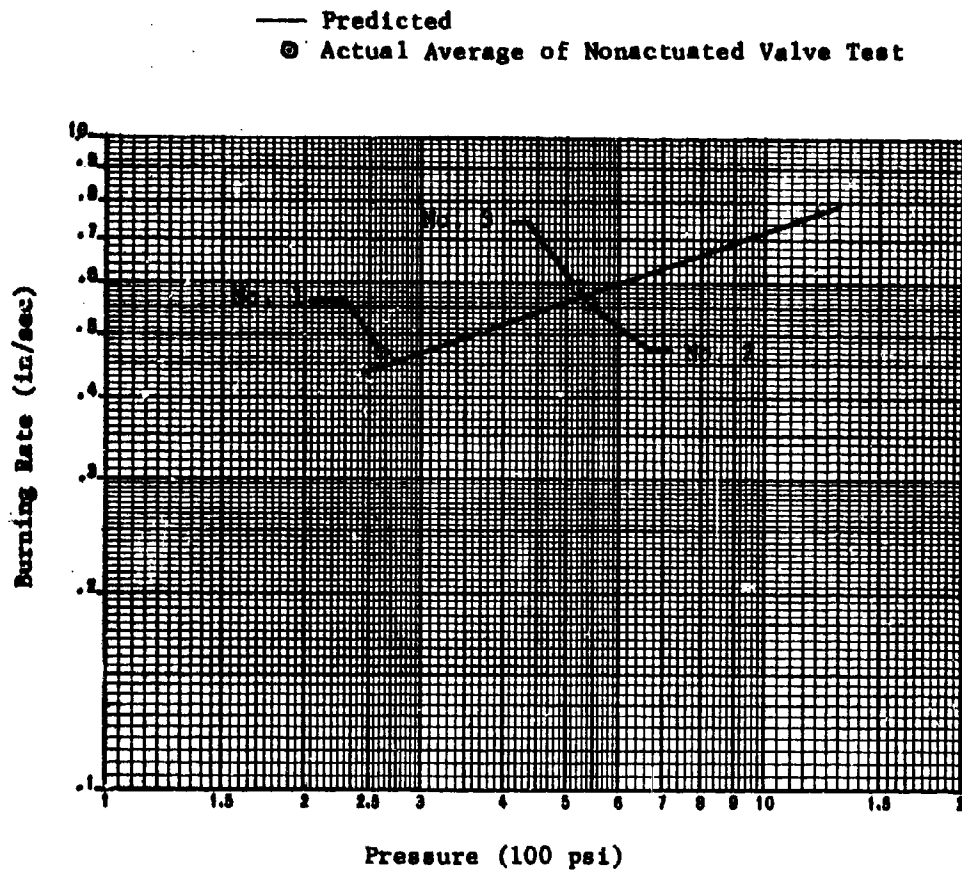
FIGURE 22

Burning Rate Curve for DDP-75 Propellant

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AFRPL-TR-65-220
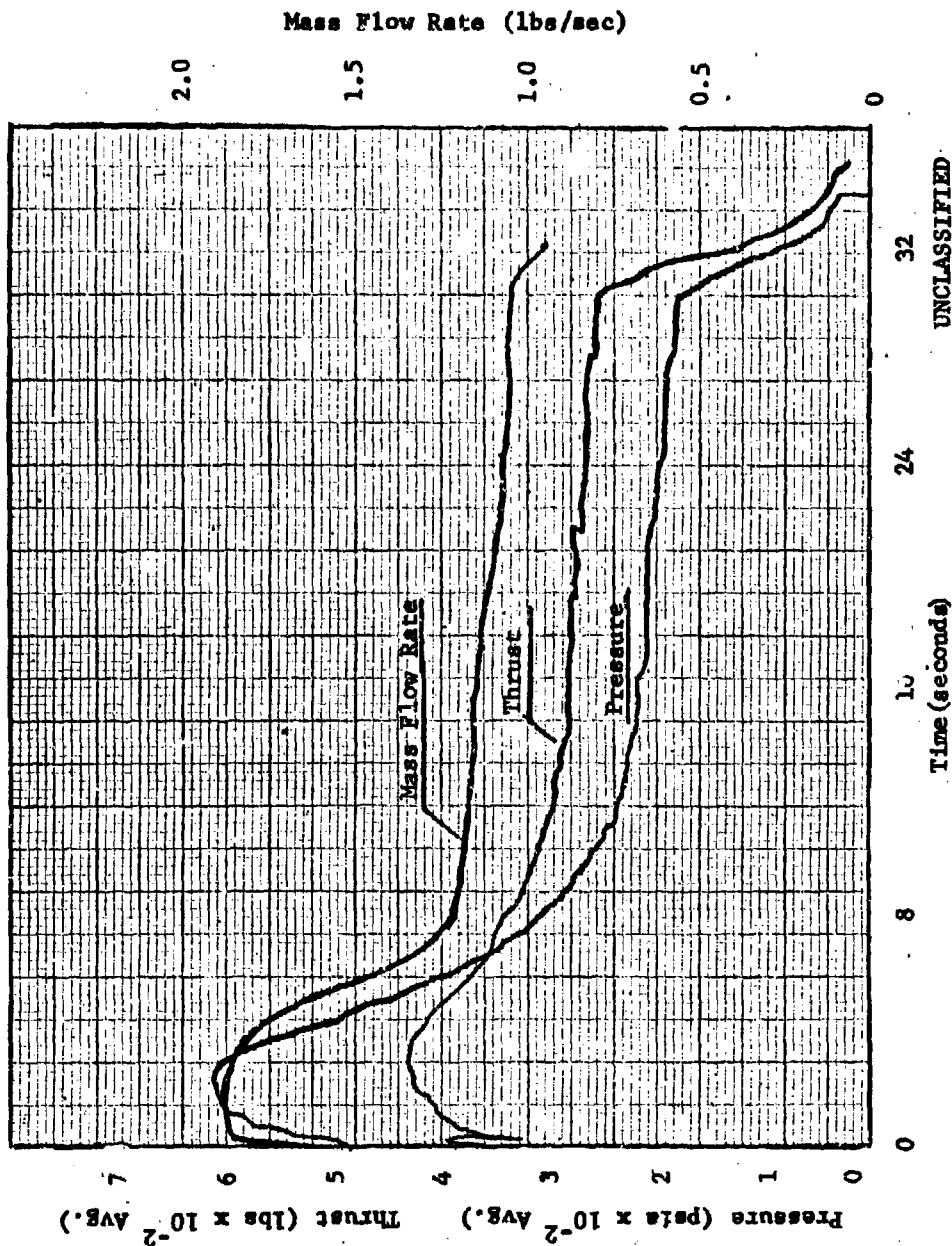
FIGURE 23

Pressure, Thrust, Mass Flow Rate for
Nonactuated Valve Firing No. 1

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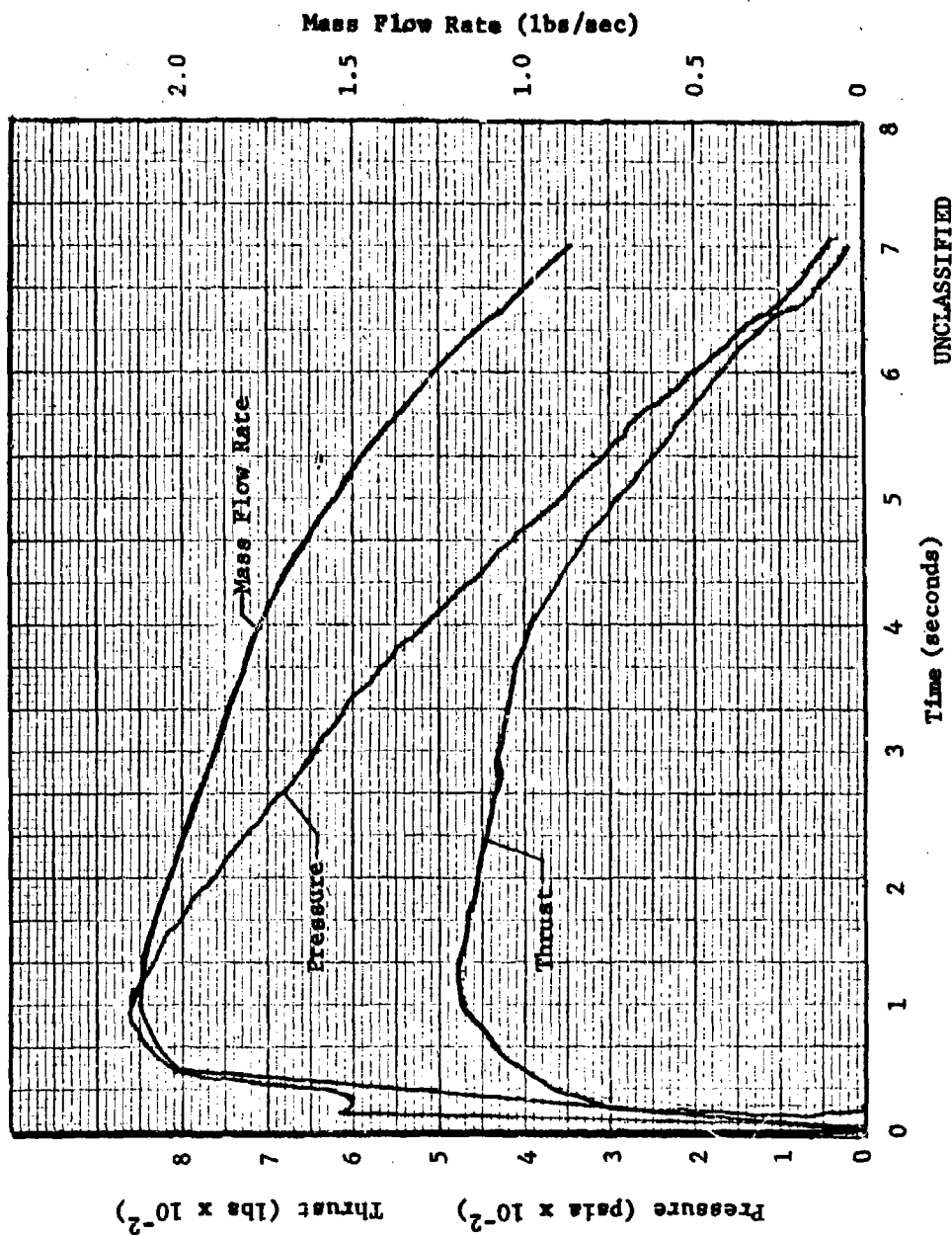
FIGURE 24

Pressure, Thrust, Mass Flow Rate for
Nonactuated Valve Firing No. 2

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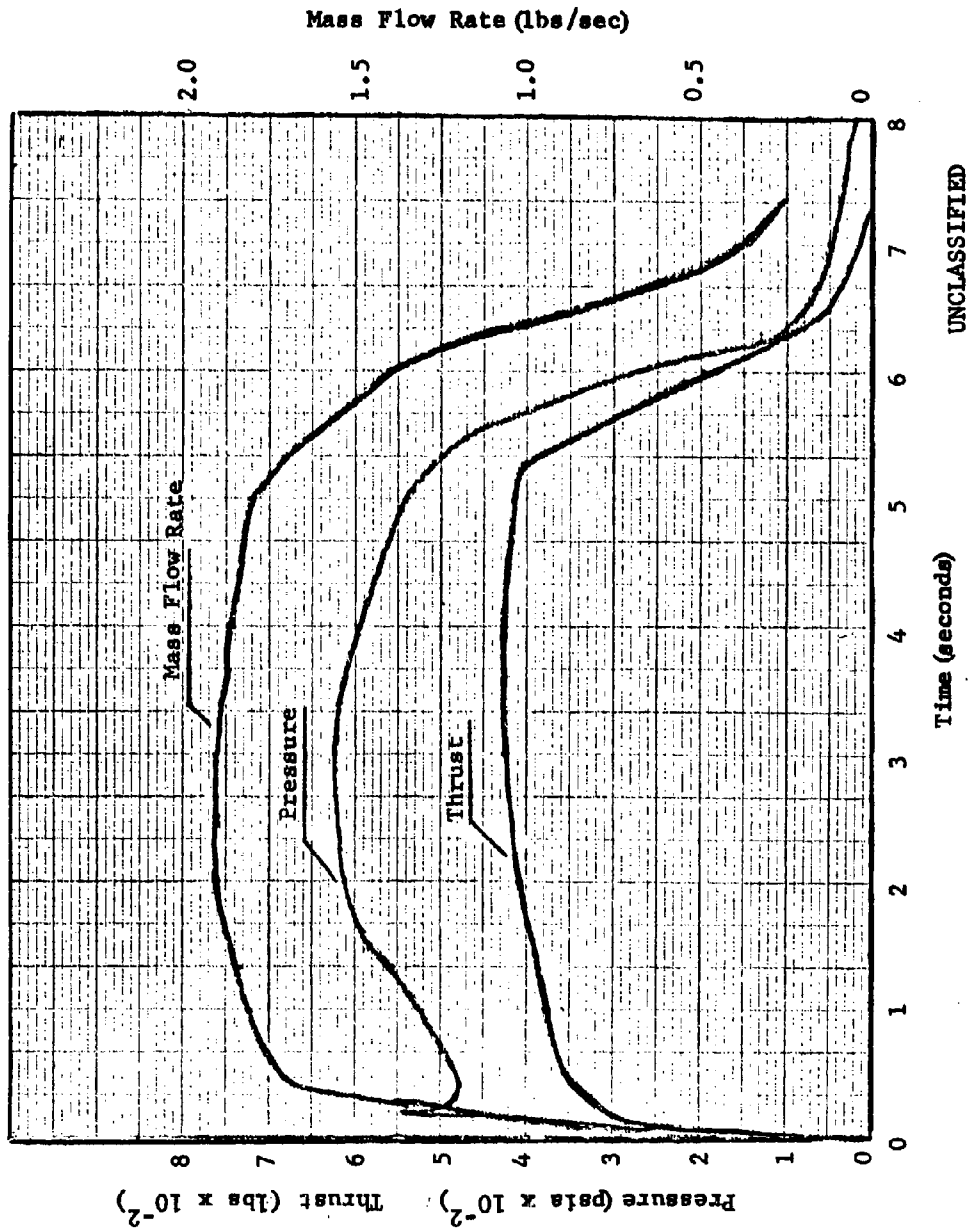
FIGURE 25

Pressure, Thrust, Mass Flow Rate for
Nonactuated Valve Firing No. 3

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F.   PROTOTYPE VALVE TEST

1.   Status

(U)   The 29-inch-diameter test motor chamber for the prototype
valve test has been conditioned and stored awaiting use. The propellant
charge and igniter are available although the propellant charge has not
been machined to final dimensions. The aft closure and subscale nozzle
are being fabricated. Valve fabrication will be initiated upon resolution
of the valve pintle design.

2.   Description

(U)   The purpose of the prototype valve test is to determine the
design adequacy of the valve TVC system components. A full-scale light-
weight valve will be mounted on a subscale nozzle and tested on a 29-inch-
diameter test motor in a 30-second static firing. The design de ils and
the description of the test arrangement are presented in Reference 1.

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G.   FUTURE WORK

(U) The following objectives have been established for the next
work period, November through January 1966:

(1) Analyze the pintle erosion which occurred in nonactuated
valve tests and determine the cause of the unpredicted
high erosion.

(2) Revise program to incorporate investigations necessary
to reduce pintle erosion by improving pintle design and
construction.

(3) Complete valve design for the prototype valve test.

(4) Complete fabrication of components for prototype valve
test.

(5) Assemble the control system and establish the actuation
duty cycle for 30-second operation.

(6) Make 30-second test firing of the prototype valve.

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AFRPL-TR-65-220

REFERENCE

(1) D. G. Drewry, et al., "Chamber Gas Secondary Injection Thrust Vector Control for High Performance Solid Rocket Motors (U)" AFRPL-TR-65-151 (ABL/AF/QPR 2), Contract No. AF 04(611)-10748, August 1965 (CONFIDENTIAL).

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5. AUTHOR(S) (Last name, first name, initial)

D. G. Drewry, G. G. McKenzie, J. D. Shipley, and J. R. Stevens

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Air Force Rocket Propulsion Laboratory Edwards Air Force Base, California

13. ABSTRACT

(U) The primary objectives of this program are (1) to demonstrate a thrust
vector control (TVC) system optimized for overall propulsion efficiency for ad-
vanced upper-stage ICBM rocket motors, and (2) to provide the data and technology
necessary for design of future TVC systems. The proposed TVC system is comprised
of four poppet valves mounted 90° apart on a submerged nozzle. The program is
divided into two consecutive phases: Phase A - Component Development and Evalua-
tion, and Phase B - System Demonstration. This technical report describes the
work performed during the second quarter of program activity.

(U) Three nonactuated versions of the submerged hot gas valve were evaluated
by static testing. The primary difference between the three designs was the
length of the dam enshrouding the centerbody and pintle in the subsonic portion of
the valve. With the exception of excessive pintle erosion, it appears that the
contractually specified criteria for valve selection can be met with the basic
three-strut-supported, open (no dam) valve. Results to date indicate that the
pintle erosion problem is not insurmountable but will require concentrated effort
to resolve.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

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